Perch to Fly: Embodied Virtual Reality Flying Locomotion with a Flexible Perching Stance *

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ABSTRACT
Many studies have proposed different ways of supporting flying in embodied virtual reality (VR) interfaces with limited success. Our research explores the usage of a user's lower body to support flying locomotion control through a novel "flexible perching" (FlexPerch) stance that provides user with leg moving ability while sitting. We conducted an observational study exploring participants' preferred usage of the FlexPerch stance, and a mixed-method study comparing the same flying experience with existing sitting and standing stances. Our results show that FlexPerch markedly increased participants' feelings of flying. However, people may not like "flying" when they really can - the freedom, feeling of floating, and novelty contributing to this sensation can also mean more effort and feeling unsafe or unfamiliar. We suggest that researchers studying VR flying interfaces evaluate the feeling of flying, and raise design considerations to use stances like FlexPerch to elicit feelings of flying and stimulation.

KEYWORDS
Virtual Reality; 3D Locomotion; Embodied Flying

INTRODUCTION
In virtual reality (VR), the user moves around in a virtual environment (VE) and sees the digital world through a first-person viewpoint. The first-person viewpoint change in VR is called locomotion. Locomotion is one of the most primitive and important topics in VR research [1]–[3]. Flying is one of the most intriguing VR locomotion types, because embodied flying (e.g., flying like a bird) is an experience that human beings have long dreamed about achieving [4]. The essential design challenge for embodied flying locomotion is providing control over navigation while also providing the user with a sensation of flying. Researchers have developed VR flying interfaces with three kinds of user stances: lying, standing, and sitting, and each of these stances has specific constraints. The lying stance puts the user in a prone position with head and limbs hanging, which causes easy fatigue. For the sitting and standing stances, the user is less likely to get fatigued. But since the user's lower body is constrained by the seat or the ground, he/she may feel less like flying.

In this paper, we proposed a new "flexible perching" (FlexPerch) stance, that provides the user with both seat support and lower body freedom. We used the Limbic Chair^{TM} (Figure 1) [5], a chair with two rotatable shells for each of the user's legs to move in pitch and yaw directions, to provide the user with separate legs movements. This chair was originally designed to keep the user in constant motion for healthy sitting. To explore how this FlexPerch stance could assist VR flying locomotion and affect people's experience, we conducted two successive studies.

Figure 1. The Limbic Chair

Study 1 was exploratory and observational, and focused on understanding people's natural use of the FlexPerch stance for VR flying. This involved exploring people's preferred navigation movement choices and considerations for the design of the FlexPerch apparatus. In Study 2, we applied the results of Study 1 to create a modified design of FlexPerch, and compared the VR flying experience with FlexPerch to that with sitting and standing stances using mixed methods. We conducted a repeated-measures experiment [6] with questionnaires and an interview to better understand how and why FlexPerch provided different VR flying experiences than the sitting and standing stances.

Our results show that the FlexPerch experience was the closest to people's imagined feeling of flying, but it was not significantly preferred by users. FlexPerch provided better feelings of floating because of the free leg movement, yet

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this feature created feelings of unfamiliarity and instability, and thus hindered some people from liking FlexPerch. Our work implies that VR flying interface designers could adopt FlexPerch, according to the design considerations we present, to provide the user with both sitting support and better feeling of floating and flying. However, this would come with some caveats, as noted in our results. Our study also points to the need for researchers studying embodied flying locomotion interfaces in VR to ensure they evaluate them in terms of effort, safety, and familiarity. Interfaces that were felt to be more effortful and unsafe created stronger feelings of flying in our study, yet effortful and unsafe interfaces are problematic in real world situations.

RELATED WORK

3D Locomotion Technique Studies

Embodied VR flying locomotion, is a kind of **3D locomotion**. There are three primary goals of 3D locomotion: exploration, search and maneuvering [7], [8]. In exploration, a user locomotes to gather information in the environment, or just locomotes for fun in a joyful or stimulating VE. Search is when the user has a specific target to locate in the VE. Maneuvering refers to a precise perspective control over a target. This may happen when the user observes an object at a different angle, in order to gain more knowledge of it. Each of these three goals may require different techniques to be most effective [8].

Locomotion techniques mostly fall into four categories [8]. **Manual manipulation** is a kind of exocentric navigation, which includes the "camera-in-hand" technique (a user's hand is shown over a map and acts as a camera specifying the imagery rendered for the display) [9] and "scene-in-hand" technique (a miniature of the environment is attached to the user's hand position) [9]. The other three categories are egocentric. The **automated** locomotion technique does not provide real-time control during travel, but does allow users to designate a target position ("target-based", e.g. [1]), or moving path before the actual travel ("route-planning", e.g. [10]). **Steering and physical locomotion** allow users to decide the real-time orientation and velocity during travel. **Steering** refers to control in which the user's body is relatively stationary. Traditional controls like the use of joysticks fit into this category. Other methods can involve using gaze [11] or pointing [12] to direct the movement direction. Steering does not provide motion cues (somatosensory and vestibular cues that suggest self-motion) to the user. **Physical locomotion** provides full motion cues (1:1 physical travel) or partial motion cues to the user [13] (e.g. "walking in place" [14], and leaning-base locomotion [15]–[17]). Physical locomotion provides the user motion cues and better self-motion [13], [18].

The embodied VR flying locomotion we focus on in this work is of the physical locomotion type, and our goal is not only to provide the user with exocentric, real-time motion-cuing navigation, but also a feeling of flying. We identify our locomotion goal as more on exploration and search, and less on maneuvering, because flying locomotion is faster and larger range compared to grounded based locomotion. We focus on moving through the environment, instead of staying in a smaller area maneuvering the viewpoint.

3D Flying Locomotion Interface Studies

3D flying locomotion allows the user to locomote in VE unconstrained by gravity and the ground, which contrasts ground-based locomotion. There are two main purposes for designing VR 3D flying locomotion interfaces: aircraft flight simulation and VE navigation. Flight simulation studies emerged in the 1930s for pilot training [19] and replicate the exact operations and environment feedback of real flights. In this paper, we discuss another purpose, VE navigation, which is to facilitate flying navigation in a VE, in terms of the accuracy, efficiency, sense of flying, etc. Studies of this purpose emerged naturally around 30 years ago with early 3D locomotion technique studied. As Blanchard said in 1993, "Nobody walks in VR, they all fly," [20] because the 3D locomotion in VEs that pioneers like him studied was just like flying: it was smooth, free and unconstrained by gravity.

Early studies in the 90s and 2000s focused on how to effectively navigate and do tasks in 3D VEs (e.g. precise viewpoint control or navigation in large areas). Ware and Osborne [21] compared "flying vehicle" metaphor, in which users navigate the VE in a egocentric perspective, to "scene-in-hand" metaphors, in which users attach a miniature of the VE in hand, and "camera-in-hand" metaphor, in which users control a camera in hand over a map to specify the display. They found the three metaphors all had their own constraints and affordances, and the "flying vehicle" performed better in conducting smooth movements. Following this work, many researchers have studied large scale area locomotion. For example, Pausch proposed a "world-in-miniature" (WIM) method [22], a hand-held miniature representative of the VE with a movable object representing the user him/herself, to facilitate navigation in a large space. A study found the WIM was useful for some common tasks in VE, but would confuse users when scene updates occurred after navigation [22]. Some researchers have studied the reasonable speed of flying in VEs. For example, Mackinlay proposed a method in which the moving speed became logarithmically slower when the user approached a target position [23]. Ware and Fleet proposed a method to scale flying speed changes in relation to the user's distance to the VE's and found users preferred sampling processes [24].

While the aforementioned research builds a foundation for our own work, none of the early flying interfaces provided motion cues to the user, and seldom did they explore the "feeling of flying", i.e. whether the users perceived an illusion that they were really flying in the VE.

Recent flying interfaces fall into two streams: **simulated VR flying**, which gives the user the scenery generated by computer simulating system (e.g. [25]–[27]), and **telepresence VR flying**, which gives the user real 360 degree imagery captured in real-time by an unmanned aerial vehicle (UAV), or drone (e.g. [28]–[31]).

In terms of user input for controlling VR flight, several methods using different stances and body parts have been proposed. The most popular method is the **lying stance** in which the user lies down with arms wide open, mimicking a bird, and tilts their **arms** and **torso** to control flying (e.g. [32]–[34]). There are two ways to achieve this interaction. One is to hang the user's body in the air and then use motion tracking technology (MOCAP, Kinect, etc.) to capture the user's gestures [26], [35]–[37]. Another way is to provide a bed-like support. It could be a simple low-cost setting like cushion seats [29], or a more tailored device like Birdly [32]–[34], a plane like platform for the user to lie on that allows whole body tilting, hand gesturing, and arm flapping.

However, because lying down is not a common position in our daily activities, the gravity applied on the neck and limbs easily causes fatigue to the user when using the lying stance [38]. As such, there also other flying control designs including **sitting** ([39]–[42]) and **standing** ([4], [25], [43], [44]) stances. These flying control designs often use **head position** to control flying (3D head joystick) [39]–[41], or sometimes the leaning of the **torso** is used as the flying control [25], [42]–[45]. (Note that the head control also involves the leaning of the torso.) There are a few studies that explore the use of **arms** to control flying. For example, Wang et al. used torso leaning to control the forward and rotation, but adopted arm raising for tilting up/down [25]. Tong et al. also used arm gestures to control flying [4]. However, they both noticed that arm use causes fatigue [4], [43]. Miehlbradt et al. [45] also found using only torso in VR flying has higher performance than using both torso and arm.

Interestingly, few VR flying locomotion studies, if any, focused on **usage of the lower body**, or the **leg**. Wang et al. [25] showed that elastic feet support that tilts based on user movement was preferred by participants over hard feet support. But their control did not involve the user's leg movement. This could possibly be explained that, in the sitting stance and standing stance, the user's legs are constrained by the seat or the floor, and in the lying stance, since it mimics a bird, the usage of body parts are often focused on the arms and torso. We address this knowledge gap in our own study and propose the FlexPerch stance which allows the user to move unconstrained from the seat and floor, and compare it with the same VR flying interfaces using standing and sitting stances.

STUDY 1

In our first study, we explored the natural use of the FlexPerch stance supported by the Limbic Chair for VR flying locomotion through an exploratory, observational study. The goal of the study was to explore how FlexPerch could be used to support flying locomotion in VR. Study 1 forms the basics of the comparison between the FlexPerch stance and sitting/standing stance in Study 2.

Method

Study 1 contained a guided experience phase, an optional free exploration phase, and an interview.

Guided Experience and Free Exploration. In the guided experience, we asked the participant to experience the FlexPerch stance for VR flying by sitting on the Limbic Chair while wearing an HTC Vive headset (Figure 2). Then without VR visual feedback, we asked participants to imagine how they would use this stance in a VR flying scenario. We gave participants a list of flying navigation instructions, and asked them to conduct navigation movements that they thought were natural and to imagine the corresponding visual scene. The flying navigation instructions included: Take off; Fly up; Fly forward (speed up, speed down); Turn (left, right); Stop and stay in the air; Spin around; Fly back; Fly down; Land. The order of the instructions matched a complete flight process; however, this order was not fixed, and the participant was allowed to jump to any step as he/she wished.

Figure 2. The experiment setting for guided experience and free exploration phases

In the free exploration phase, which was more exploratory and unstructured, we had an optional free exploration in which the participant stayed on the Limbic Chair, reflected on the flying movements, and moved however they wanted. Participants usually commented from an overall point of view and proposed new ideas on the interface design. During the study, when any interesting design ideas were mentioned, we applied them to the experiment for later participants to test them out. Thus, our study was designed to be exploratory and iterative and not intended to be carefully controlled in terms of exact repeatable conditions.

Participants were asked to "think out loud" while doing the movements. Movements were video recorded and the experimenter also took notes during the experience.

Interview. After participants finished the guided experience and free exploration phase, they participated in an interview.

Here, they were first asked about basic information (height, experience using the Limbic Chair, and experience in VR research, development, or gameplay). Then they were asked open ended questions regarding the quality of the experience (comfort, safety, enjoyment, intuitiveness, ease of learning, ease of control), the most liked/disliked part of the overall movement experience with FlexPerch, and the most liked/ disliked navigation movement on this stance. The interview was audio recorded, and the experimenter took notes.

Participants. Since we relied on participants to give insights on the flying interface design, we wanted capable participants who were experienced in VR/3D interface design. We invited five VR researchers (all male; age 25-48, M = 33.6) from our department. They had four months to over 20 years of VR gameplay, development or/and research experience. They had used the Limbic Chair a few times before the study, but had not explored it systematically.

Data Analysis. We performed open coding on all of the interview data (annotating by sentence), followed by axial coding on all participants over every interview question to generate categories about people's opinions of FlexPerch. Example codes include "feeling", "mechanism", "device", etc. Axial groupings included "freedom", "floating", "rotation", "comfort", "safety", etc. Lastly, we performed selective coding to draw out our most interesting findings, which are presented in our results section.

The analysis we used for the video data was similar to text-based coding, where we extracted key themes of each participants' body movement choice for each navigation instruction, and generated higher level themes of movement choices generally preferred for each navigation instruction and issues arisen, based on the visuals in the video. The participants' comments according to their movement choices were coded to help with understanding the movement choices and inspire new solutions.

One researcher performed all stages of data coding. Themes were iteratively discussed with additional researchers on the project and this helped to refine and revisit the coding. Video analysis was used to investigate participants' movement choices, and the think aloud data and the interview data revealed participants' preferences and issues with movement choices. We describe the findings in the following sections.

Participants' Navigation Movement Choices

We discuss the participants' navigation movement choice by looking at the usage of four body parts separately: upper body, legs, arms, and head.

From our observations, when using FlexPerch for VR flying locomotion, the **upper body** was the most used body part. In the forward, backward, and turning navigation movements, participants preferred to lean their upper body to the corresponding direction. In the turning movement,

Figure 3. Hard feet support (left) and soft feet support (right) in the free exploration phase.

participants preferred to either lean, or rotate the upper body (or lean and rotate the upper body at the same time) to the turning direction. And in the upward and downward movement, the participants would stretch and crunch their upper body.

We also noticed that, for the leaning back movement, because the participants' lower body was not stable in the leg-free movement, and that the Limbic Chair did not have a backrest, participants had to use their abdominal muscles to keep their balance, which was not a common everyday activity and may cause discomfort. Moreover, participants were afraid of losing their balance and falling backwards. We noticed this concern and moved the seat against a wall for the second participant onward. This reduced participants' concerns, but they still felt unsecured, because they could not see the back wall when wearing the VR headset.

Leg usage was the most unique part of the FlexPerch stance. From our observations, the **legs** were used to support upper body movement. The advantage of FlexPerch was shown in the *turning* movement. Three participants (P3, P4, and P5) discovered that it was natural to raise up the leg on the same side of the turning direction, and to press down the other leg on the opposite side (e.g., when rotating to the left, the left leg was raised up and the right leg was pressed down). So the leg movement looked like a "skiing" movement when a person uses one leg to push his/her body to a side to rotate. In this way their upper body could tilt or rotate more to the direction. P4 and P5 reported that this skiing movement was their favorite navigation movement. We noticed that this was a unique movement that a user could conduct with the FlexPerch stance, but hardly with standing or sitting stances.

In the *upward* movement, when the participants stretched their upper body up to reach higher, they also pressed down and stretched their legs straight. In the *downward* movement, when participants crunched their back, they would relax and drop their legs down to form a natural oblique degree (P1, P2, P3 and P5), or raised their thighs to a horizontal level to lower their upper body down (P4). For the *forward* and *backward* movements, participants did not use their legs specifically; instead, their legs were naturally hanging.

When navigating forward, since participants leaned forward, the legs were also tilted down and thus touched the ground. This reduced the feeling of flying, as reported by the participants. Some struggled to lift their legs off the ground

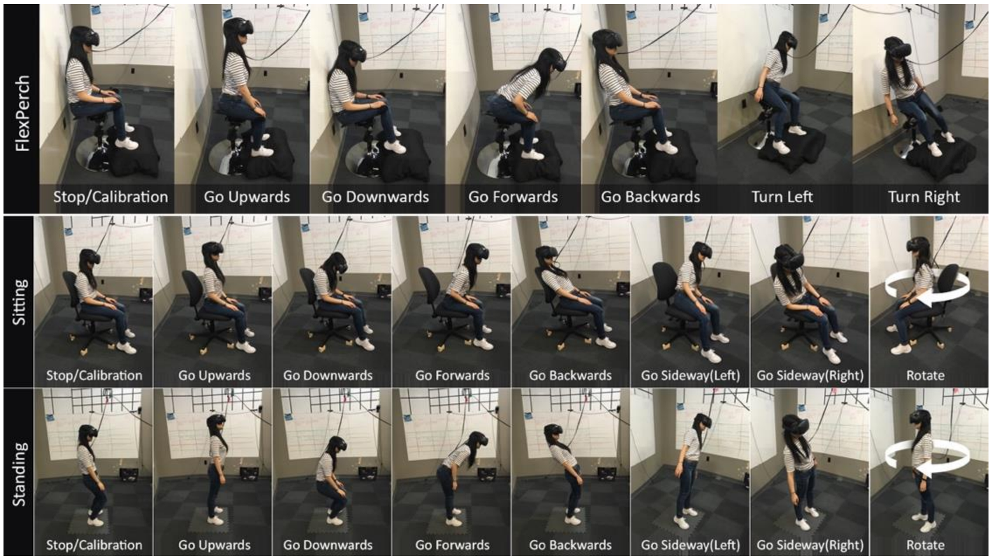

Figure 4. The flying navigation controls for the FlexPerch, sitting, and standing stances.

while crunching their upper body. This was not only uncomfortable, but could cause participants to slide down from the seat, because the legs were mobile in the FlexPerch stance. Thus, it was hard for participants to keep their balance. This problem was more obvious when participants leaned more to simulate the speeding up situation in the forward navigation movement. This problem also happened in forward navigation when participants stretched their legs.

For this problem, the second participant mentioned that he wanted some support under his feet. So for the later 3 participants, we asked them to experience two kinds of feet support in the free exploration phase: hard support, which was a cardboard box, and soft support, which was a stack of pillows, under the participant's feet (Figure 3). We found that the hard support did not solve the problem because it reduced the feeling of flying more than without it, and it limited participants' leg movements. However, soft support received all positive feedback because it provided a certain degree of support from the feet, so that the user wouldn't slide down, and a degree of movement for the user to still move their feet. It was described by the participants as "felt like a cloud", "felt like flying" and "had better control".

The remaining two of four body parts were used in a way that made them less important in terms of overall locomotion. The **arms** were used for flying gestures. For example, one participant made a "super hero" flying gesture (stretching one arm forward and putting another arm down) for flying forward. The **head** was seldom used, e.g., four participants (P1, P2, P3, and P5) look down with their head in order to navigate down.

STUDY 2

Study 1's results suggested valuable uses of FlexPerch in a VR flying context: leaning the upper body, using skiing-like turning, and using back wall support and soft feet support. Based on these findings, we conducted a second study to see if and why FlexPerch could create a better VR flying experience compared to the same flying interfaces based on the sitting stance and the standing stance. We excluded the lying stance in the comparison because we were more interested in the user stances that were closer to the normal stances that users may use to control their body daily. From our exploration of FlexPerch in Study 1, we found FlexPerch provided some interesting movement choices that made the flying locomotion more natural. The unique leg freedom of FlexPerch contributed to the comfort, ease of control and intuitiveness for the VR flying locomotion. We also identified some pitfalls of FlexPerch. In Study 2, we adjusted the VR flying locomotion interface with FlexPerch for use in a real VR flying application. Our hypothesis was that FlexPerch would provide a better VR flying experience - in terms of ease of control, feeling of presence, and simulator sickness symptoms - than the sitting and standing stances.

Method

We adopted a mixed (quantitative and qualitative) research method in the second study.

Participants. A total of 18 participants (age: M = 21.6 years, SD = 2.68, range = 19–29, 8 males and 10 females) were recruited from the subject pool of a large public university in Canada and received partial course credit or compensation for their participation. Participants wore an HTC Vive during the experience. Before, at the end of, and after the experiment sections, the participants left the experiment area and worked on a different table on the questionnaire with another computer provided.

Flying Control for the Three Scenes. From Study 1, we knew that it was natural for people to use their upper body and lean in order to control flying. We adopted the same leaning-based flying control developed by Hashemian et al [16], [17] for the flying controls of all three stances to make the conditions comparable. This leaning-based flying control allows the user to lean his/her upper body in the direction they want to fly. The more the user leans, the faster they fly. A speed limit was applied to prevent the user from moving too fast. The difference of the controls for the three stances was the dynamics of the user's lower body. The flying navigation control for each stance is illustrated in Figure 4.

For FlexPerch, the Limbic Chair was put against the wall, with the base 5-10 cm away from the wall, according to the participant's height so that he/she had space to move backwards, but still be able to touch the wall if he/she went too far backwards. A stack of pillows was put under the participant's feet to provide soft support and balance while still ensuring leg freedom. To fly up, the user would tilt the shells, step down on the pillow to push his/her hip and whole body up. To go down, the user tilted the two seat shells reversely, lowered his/her hip, and bowed the back. To fly forward and backward, the user leaned the body to the direction. To turn, the user conducted a skiing-like movement. For example, to turn left, the user tilted the upper body to the left side, lifted the left leg (tilting the shield up) and pressed the right leg down (tilting the shield down). The pillow supported the legs to hold the balance when tilting. For the sitting stance, the user sat on a normal swivel chair. The chair's wheels were replaced by wooden blocks to prevent it from moving. For the standing stance, the user stood on a 60x60cm pad to prevent the participant from walking around. For the sitting and standing stances, the user could move upwards, downwards, forwards, backwards, and side ways by leaning to the corresponding direction. They could also rotate by rotating their full body (Figure 4). To fit each user's body size, a calibration process was needed before flying. For this, the user needed to find a middle position that allowed them to get higher and lower.

Procedure. Before the experiment sections, the participant was asked to fill in a pre-experiment questionnaire to give demographic information (gender, height, gaming experience etc.). Then the participant participated in a repeated- measures experiment comprised of **three sections** with the three flying stances. In each section, the participant finished a training session to calibrate initial position and practice the flying control. After the participant felt that they had mastered the flying control, they completed two study tasks. The goal of the two tasks was to motivate the participants to actively use the interfaces in VR, so we designed the first task to involve exploring VE and the second task to involve searching for an object. The tasks were meant to be interesting and also align with common VR flying tasks. In the **first task**, the participant acted as a tourist, exploring the virtual scene and taking two photos.

Figure 5: Row 1: The photo taking task (left) and the chest hunting task (right). Row 2: experiment scenes of Section 1 (Snow Mountain), Section 2 (Lake), and Section 3 (Night). Pictures were taken in the real experiment by participants.

The photos would be sent to the participant after the experiment as a souvenir from the trip. In the **second task**, the participant needed to find a hidden treasure chest in three minutes. In this task, the participants had to actively survey the whole area to locate the treasure chest, and then make more precise movements to approach the chest and open it.

The order of the interfaces was shuffled with full permutation to counterbalance the carryover effect. To maintain the participant's interest for exploration, three different environment scenes were used for the three sections. Due to the complexity of shuffling the scene order, every section used a fixed scene.

Right after each section's VR flying experience, participants filled in a questionnaire evaluating the experience. The questionnaire contains questions for **seven rating items**: ease of control, feeling of presence, simulator sickness, joy, likeness to flying, safety and comfort.

- ***Feeling of presence***: evaluated using the Igroup Presence Questionnaire [46], rated from 0 (worst) to 10 (best).
- ***Ease of control***: We used two questionnaires to evaluate the ease of control. The first set of questions are from the control factor questions from Witmer and Singer's Presence Questionnaire that evaluates the user control in terms of degree of control, anticipation of events, mode of control, and VE modifiability [47], rated from 0 (worst) to 10 (best) . The second questionnaire is the NASA Task Load Index, which evaluates the perceived workload of tasks or a system in terms of mental demand, physical demand, temporal demand, overall performance, effort and frustration level [48], rated from 0 (worst) to 10 (best).
- ***Safety, comfort, joy, and likeness to flying***: We also asked participants to rate their experience in terms of safety, comfort, joy, and likeness to flying, each on a 0 to 10 scale.

We collected the questionnaire data using a spreadsheet, showing the questions as rows, three sections as columns, in order to enable participants to easily compare and adjust their scores for each section. To make it easier for the participant to go through the long list of ratings without being confused by the scale, we consistently used a 0-10 scale for all the rating questions (except the simulator sickness, because its suggested use is a 4-point discrete scale rather than a continuous spectrum from the worst to best). For all these scales, 10 was the best rating.

After all the three sections of the experiment, a semi-structured interview was conducted. The interview included both quantitative close-ended questions and qualitative open-ended questions. The closed questions included **three voting items**: participants chose their most liked stance, the most disliked stance, and the stance that is closest to the participant's imagined feeling of flying. The open-ended questions included "why" questions for the voting questions, the differences between FlexPerch and the other two stances, and follow-up questions.

Data Analysis. We collected valid data from 18 participants. The quantitative data include ratings from the questionnaires and voting data from the interviews. We analyzed the rating data with 1-way repeated-measures ANOVA on the stance factor (FlexPerch, sitting, standing), and the voting data with its distribution and chi-square test of goodness-of-fit.

For the qualitative (interview) data, we firstly performed line-by-line open coding and generated initial themes (e.g. "comfort", "safety", "new and fun"). Following this, we performed axial coding by grouping all the themes by "pros", "cons" and by grouping participants who shared the same preference in voting questions. We integrated the two groupings to investigate the relationship between people's preferences and their opinion themes. Lastly, we performed selective coding to draw out our most interesting findings that are presented below.

Affordance Qualities

The rating data included the affordance quality items of ease of control, feeling of presence, simulator sickness, joy, likeness to flying, safety and comfort. For each item, we used the Shapiro-Wilk test to exam the assumption of normality (all *p*s > 0.05), and Mauchly's test to exam the assumption of Sphericity (all *p*s > 0.05, other than the item of joy). For joy, the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.68$). Then we conducted a one-way ANOVA to examine the variation between the three groups. Only three items showed significant difference: simulator sickness ($F(2, 34) = 6.71$, $p = 0.0035$), safety ($F(2, 34) = 4.64$, $p = 0.02$), and comfort ($F(2, 34) = 7.13$, $p = 0.0026$), as shown in Figure 6. Feeling of presence, ease of control, joy, and likeness to flying did not show significant difference. We conducted Tukey HSD post-hoc test and calculated Cohen's d for these three items. For **simulator sickness**, although all interfaces gained low scores (all means < 0.5, 0-3 scale), the sitting stance ($M = 0.14$, $SD = 0.16$) had significantly ($p = 0.0024$, $d = 0.71$) lower scores than FlexPerch ($M = 0.32$, $SD = 0.28$), meaning that the sitting stance caused the least sickness to the participants. For the rating of **safety**, the sitting stance ($M = 8.44$, $SD = 1.65$) had a significantly ($p = 0.013$, $d = 0.85$) higher score than the standing stance ($M = 8.44$, $SD = 1.65$). **Comfort** wise, the sitting stance ($M = 7.44$, $SD = 1.95$) was rated significantly higher over both the standing ($M = 5.11$, $SD = 2.74$) ($p = 0.0042$, $d = 0.95$) and the FlexPerch stance ($M = 5.11$, $SD = 2.74$) ($p = 0.0121$, $d = 0.84$). Based on the aforementioned analysis, we can reject our hypothesis that the FlexPerch stance brings more ease of control, feeling of presence, and less simulator sickness. The sitting stance performed the best in simulator sickness, safety and comfort. The standing stance was the least safe and uncomfortable stance, while the FlexPerch stance caused the most simulator sickness of the three stances.

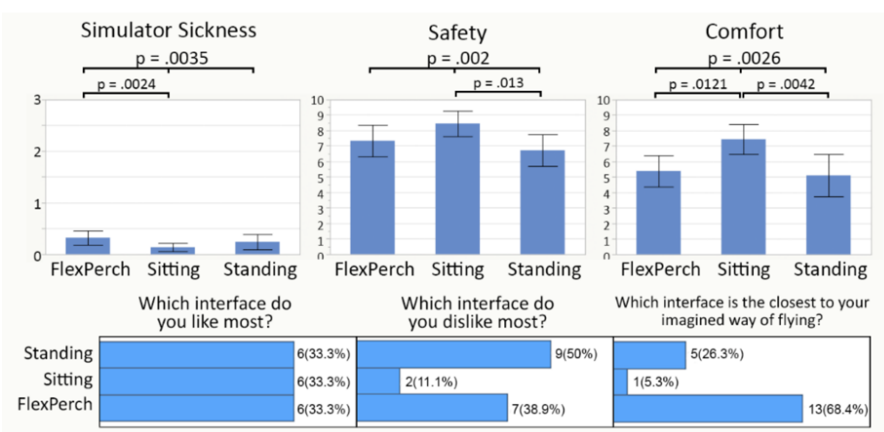

Figure 6. Row 1: means and 95% CIs of significant items of rating data. Row 2: distribution of the voting data (count and %).[1]

[1] For the third voting (closest to flying), there were 19 votes in total, because one participant voted for both FlexPerch and standing.

The Closest Feeling to Flying and Preferences

Our data showed that the three stances were equally liked by the participants (each stance received 6/18 votes) (Figure 6, bottom). However, the **sitting** stance, which earned the best score in the rating result, was the least disliked stance (2 votes, 11%). The **standing** stance performed the worst in the rating result, and it was indeed the most disliked stance in the voting (9 votes, 50%). The **FlexPerch** stance received more votes (13 votes, 68%) than the other stances as the stance that was closest to the participant's imagined feeling to flying. A chi-square test of goodness-of-fit confirmed the voting for the "closest feeling to flying" was not equally distributed ($X^2(2, N = 18) = 12.64$, $p = 0.0018$).

Interestingly, we found that there was a relationship between the like/dislike preference of the stances and the participants' choice of the closest feeling to flying: 1) all participants who chose the FlexPerch stance as their favorite interface also thought the FlexPerch stance was the closest to flying (P02, P01, P04, P05, P16, and P18) –we call this group of people the green group, for easier reference and visualizing their distribution in the opinion table (Table 1) later; 2) among the 7 participants who disliked the FlexPerch stance, 5 of them (P06, P10, P13, P15, and P17 – the red group) thought the FlexPerch was not the closest feeling to flying; 3) participants that neither chose the FlexPerch stance as their favorite, nor as their disliked stance (P03, P07, P08, P11, and P12 – the purple group), all thought that the FlexPerch stance provided the closest feeling to flying. In fact, even for the participants who disliked the FlexPerch stance the most, two of them (P14 and P09 – the orange group) still voted the FlexPerch stance as the closest feeling to flying. Thus, we noticed a strong tendency that most participants thought the FlexPerch stance provided **the closest feeling to their imagined feeling of flying**, which holds true even if some participants might prefer the other control interfaces.

The Pros and Cons of FlexPerch

Table 1 presents participants' opinion themes on FlexPerch extracted from the interviews, together with their participant numbers. We noticed that some likes and dislikes were related. For example, P02, P05, P12, and P07 liked FlexPerch because it provided **more control**, but P08, P14, P15 and P10 disliked it because it **was hard to control**. In the table, we put these related themes in the same row.

Leg Movement, Feeling of Floating and Turning Mechanism

Why did most people (green, purple and orange) choose FlexPerch as closest to flying? There were three major reasons: **leg movement, the feeling of floating, and the turning mechanism**. We found the **leg freedom** was the top reason why participants chose FlexPerch as closest feeling to flying, e.g., when asked the reason for choosing FlexPerch as closest to flying, P07 said "because my legs can move"; P08 said "I can use legs to cooperate with my upper body".

Pros (What people like)		Cons (What people dislike)	
Comfortable	**P2, 5**	Uncomfortable	**P13, 6, 14, 12, 15, 11**
Safe	**P2**	Unsafe	**P8, 14, 18**
New and fun	**P2, 1, 16, 4, 3**	Not familiar	**P15, 8, 14, 3, 7**
Natural	**P4, 8, 17, 18**	Not natural	**P15**
Control and Movement	(More control) **P2, 5, 12, 7** (More movement) **P15, 3, 5, 18, 9**	Control and movement	(Hard to control) **P8, 14, 15, 10** (More complicated movement) **P13, 14, 15**
Floating	**P11, 14, 16, 18, 9**		
Turning (like)	**P8, 3, 5, 4, 16, 12**	Turning (dislike)	**P13, 15, 17, 9**
		Slow	**P13, 10, 15, 17**

Table 1. Opinion Themes towards FlexPerch.

Another important reason was that the participants felt a **feeling of floating** when in FlexPerch, e.g., P09 mentioned that "I feel I'm swing in the space… My legs were in the air suspending, I felt floating". We recognized this effect as a result of the leg movements and the soft support provided by FlexPerch. The **turning mechanism** was also a commonly mentioned reason. We designed the turning so it involved not going directly sideways, but instead involved slowly rotating while the user tilted their body to the side with legs in a skiing-like movement. In the VE, the turning movement would be often combined with slightly moving forward, making a curve like movement. These participants found this turning mechanism natural and like flying, e.g., P03 said "I have to use one side of the body to turn – more like flying" and P09 mentioned "turning is also like how I would fly".

User's Relationship to Novelty

If most people thought FlexPerch was the closest to flying, why did some of these participants (purple and orange) not choose it as their favorite stance? We investigated these participants. Their main reason for choosing the sitting stance as their favorite was that the sitting stance was more **familiar** to them, and it was more **comfortable**. For example, P07 said, "I'm more used to the normal chair… (FlexPerch is) a bit complicated"; P08 said "the sitting stance is more comfortable… the FlexPerch is not as familiar". These participants' main reason for choosing the standing stance (P03, P14, and P09) was that they preferred its **bigger range of torso movement**, and thought it was **easy**, **and familiar**. For example, P03 said the standing stance "has no chair to limit my freedom" and "has bigger moving range"; P14 mentioned the standing stance was "simple and easy" while FlexPerch "was high-tech, new… but not familiar."

Overall, we found that "**unfamiliarity**" was the largest threat for FlexPerch to become people's favorite interface. This was likely due to the **novelty** of this stance– none of the participants had ever experienced it before the experiment. We found this kind of novelty reflected in almost every participant's response. However, FlexPerch likers (P02, P01, P04, P05, P16, and P18) mentioned this **novelty** in a positive way - they thought it was "new and fun". E.g., P02 said "it was my first-time experience (of FlexPerch). It was interesting". Thus, we found that the **relationship to the novelty** of FlexPerch was the watershed for the participants to favorite FlexPerch, or not: if the participants liked the novelty, they liked FlexPerch the most. If the participants did not, they may choose other stances as their favorite.

Incompatibility to the Turning Mechanism

Finally, why did a small group of people (the red group) not consider FlexPerch as closest to flying, and meanwhile all dislike it? We found the incompatibility to the **turning** mechanism (either considering it as **unfamiliar** or too **slow**) made people dislike FlexPerch the most. We look at this group of people. The most frequently mentioned reason for disliking FlexPerch was again the **turning mechanism**. These participants either thought the **turning** was **slow**, or **not familiar** with the skiing-like turning movement. For example, P13 said "it's not natural to turn". P17 thought FlexPerch was "hard to turn. I move slow." P15 said "turning was slow… It's not familiar, so hard to control." On the other hand, we also noticed the participants who complained about the turning and being slow were mostly the participants who did not choose FlexPerch as the closest feeling to flying (as shown in Table 1).

DISCUSSION

This study considered a new stance (FlexPerch) that is between the existing stances of standing and sitting for VR flying locomotion. We hoped it would overcome the lower body constraints noticed from the standing and sitting stance, and provide the user with an improved VR flying experience. We found that this stance can bring more feelings of flying to the user when flying in VR. This feeling of flying was closely related to the sense of floating, that came from leg movements with soft feet support and the turning mechanism provided by this new stance.

Feeling of flying and Competing Effects

Previous studies on VR flying locomotion interfaces focused mostly on the effectiveness of task completion time and accuracy (e.g. [40]), and usability issues like ease of control, comfort, motion sickness, intuitiveness, fatigue and fun (e.g. [39]). But those features are all common with grounded-based VR locomotion interfaces. Few had explored the "feeling of flying" that users perceive, which is unique about VR "flying" locomotion. This might be because previous studies regard the feeling of flying as a part of other conventional usability features (like presence). But that is not true, because in our study, our participants gave different evaluations to the feeling of flying for the FlexPerch interface than other usability features. As such, we suggest that the feeling of flying should be considered separately in the evaluation of a VR flying interface.

The study from Cherpillod et al in 2017 [34], the only study we know of that had cast light on the user's feeling of flying in the flying experience, found that their lying-based interface provided greater feelings of flying than a hand-held remote controller. However, they did not explore further how the interface provided the feeling of flying, and did not compare the feeling of flying between interfaces that are all embodied and provide motion cues. Our study provided a deeper understanding of the feeling of flying that users perceive in a VR flying experience. Our results showed a disconnection between "close to the feeling of flying" and "preferred experience of flying". In theory, this disconnection could have two possible reasons: 1) our participants may not like flying, when they really can; and, 2) our participants liked the feeling of flying, but they thought other factors were more important. We argue that the reason is a mixture of the two.

We argue part of the reason for this phenomenon is that people may not like flying, when they really can. As indicated in our results, leg movement gave participants more freedom, but also required more effort to keep one's balance. Similarly, the leg suspension introduced the feeling of floating, but also the feeling of being unsafe for some people. Moreover, some participants thought the novelty of the FlexPerch stance was new and interesting, while other participants considered the same novelty as unfamiliar and weird. So we see that there are some **competing effects** inherently bonded with embodied flying experience. There are benefits to the two different options and we need to offer a balance: being safe and conservative, or increasing the embodied sensations of flying, which implies not safely landing on solid ground, and operating an interface that is novel as it is not an interface that most people are familiar with. Moreover, we feel that when researchers evaluate VR flying experiences they should do so by moving beyond conventional navigation interface criteria: when a VR flying interface is simply a tool to navigate a 3D space effectively, we can use the criteria of effort, safety, and familiarity; but when we design a VR flying interface for providing the user with the embodied feeling of flying, we shouldn't rely merely on these criteria. Instead, we should consider the feeling of floating, the feeling of freedom, the stimulation, and directly the feeling of flying that the participants perceived, according to our design goals.

Flying Speed and Turning Mechanism

In our study, we found that flying speed and turning mechanism played an important role in participants' evaluations of the flying experience and are the main reason that some participants disliked FlexPerch. Most participants who disliked it the most mentioned that it was because they thought the **flying speed** of FlexPerch was too slow. But the participants who did not choose FlexPerch as the most disliked interface never mentioned speed issues. Our results also showed that the same **turning mechanism** was both the reason why some participants liked FlexPerch the most and some others disliked it the most. However, few studies had ever focused on the flying speed and turning mechanism, and no one has provided an analysis of the relationship between flying speed and the flying experience or between the turning mechanism and the flying experience. Based on Study 2's results, we hypothesize that turning mechanism is a personal preference, but the speed of flying is related to the participant's height, previous VR experience or gaming experience, and can be customized by it to provide a better experience. Additional studies could be done to explore these two aspects.

Design Considerations

Here we provide design considerations for embodied VR flying interfaces using FlexPerch. First, we feel it is important to *take the feet off solid ground and free the legs to provide a feeling of flying in VR flying locomotion*. This corroborates prior work showing that providing a cognitive-perceptual framework for "movability" (by suspending the user's feet so they no longer touch solid ground) could enhance users' illusion of self-motion [50]. One could leverage leg movements allowed by FlexPerch, especially for forward and turning navigation movements. One could also allow the user to press down their legs when they lean forward to fly forward, raise one leg up, and step one leg down (like a skiing movement) to tilt their body to the side to conduct a turning movement.

Second, designers could *use soft support under the user's feet to help them keep their balance while still having a sense of floating*. Soft feet support could prevent the user from sliding when they lean forward or reach up with their upper body, while still providing the freedom to move one's legs.

Third, designers should *be aware of the threat to safety that may be introduced with stances like FlexPerch*. It's harder for the user with a VR HMD to be aware of their body position in relation to the physical environment. When using stances like FlexPerch, in which the user's body position is more dynamic and the user can have a larger range of lower body movements, the designers should concern themselves more with safety threats that may exist. In our study, we used a back wall to help reduce the concern of falling backwards and ensure the user could not fall backwards. But from our observations, the backwards movement was seldom used by the participants in the navigation movement, so we speculated that backwards movements could be disabled to address such safety concerns.

Fourth, designers could *use stances like FlexPerch to elicit feelings of flying and stimulation.* FlexPerch performed the best at providing users with the feeling of flying compared to sitting and standing stances. This feeling is related to feelings of thrill and stimulation, similar to how roller coasters provide stimulation and enjoyment in amusement parks. However, if the design goal is to provide fast learning, stable and easy VR flying control (e.g. [45] drone tele-operation that requires robust and reliable control interfaces) the sitting stance is better, as indicated by our results.

Limitations

We identify four limitations for our study. First, Study 1 only recruited VR interface researchers as participants. Although experts could provide more professional design advice, their comments might be affected by their previous VR interface knowledge, instead of being purely induced by FlexPerch. Different insights could have been revealed if we had also included novice users. In addition, requiring participants to be experts constrained our sample size of Study 1. So although we observed a number of repeated responses on the preferred movement choices, future research is needed to investigate the generalizability of our findings about best uses of FlexPerch for embodied VR flying.

Second, although we explored the influence of FlexPerch on the VR flying experience, we haven't yet used it as an active control, i.e. using leg movement to direct flight navigation, which might make the effect of FlexPerch more obvious. Further studies should explore active control with FlexPerch.

Third, although we considered training for FlexPerch in both studies, we still noticed that some issues might be resolved by better adjusting sitting posture (e.g. the buttock stuck issue may be avoided if the user sat further back). There could be longer pre-experiment training for participants to master FlexPerch's novel movements, or we could consider movement experts (e.g., dancers) to be participants.

Fourth, our study compares FlexPerch to generally-used stances, so we did not add a pillow to standing and sitting stance. Although we found FlexPerch introduced more feelings of flying, we did not investigate how much the flexible sitting and pillow contribute separately. Further studies could look at this.

CONCLUSION

We explored the FlexPerch stance for embodied VR flying locomotion. Our design is the first to leverage leg movement in a VR locomotion control study. Our results showed that FlexPerch provides more feelings of floating with its leg movement, soft feet support, and turning mechanism. This increases the feeling of flying compared to existing sitting and standing stances. We suggest that researchers studying VR flying interfaces evaluate the feeling of flying, and be aware of competing effects, (e.g. more movement freedom may mean more effort, novelty can also mean unfamiliarity), according to the design goal. Our findings raise new considerations for VR flying locomotion designers to use FlexPerch for embodied VR flying locomotion interfaces.

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