Leveraging Shared Control to Empower People with Tetraplegia to Participate in Extreme Sports

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ABSTRACT
Outdoor recreation improves quality of life for individuals with tetraplegia, however providing safe opportunities to engage in these sports has many challenges. We describe the iterative design and field evaluation of Tetra-Ski, a novel power-assisted ski chair. Users control Tetra-Ski with a joystick or Sip-and-Puff controller either independently or collaboratively with a tethered skier through our novel shared-control scheme. We also developed a training simulator to help prepare users prior to their skiing experience. A field study with eight participants and interviews with three trainers who used Tetra-Ski showed that Tetra-Ski is usable, enjoyable, and that the experience has a positive psychosocial effect on users. Furthermore, the shared-control scheme developed for Tetra-Ski proved crucial for supporting the unique abilities of different users, suggesting that a shared-control approach could enable broader access to less-dependent forms of outdoor recreation in the future.

Author Keywords
Adaptive skiing; tetraplegia; spinal cord injury/disorder; shared control; ski chair; Tetra-Ski

ACM Classification Keywords
• **Human-centered computing~Accessibility technologies**

INTRODUCTION
In addition to traditional medical and physical needs, there is evidence that psychological factors play a significant role in the quality of life of individuals with tetraplegia, such as those with spinal cord injury/disorder (SCI/D) [24]. One review found "considerable evidence for the role of psychological factors in the [quality of life] of persons with SCI. Perceived control, a sense of coherence, self-worth, hope, and purpose in life are most consistently associated with [quality of life] after SCI" [14]. This applies to individuals with a range of SCI/D, including complex injuries that result in tetraplegia. Accordingly, there is a concerted effort to develop opportunities to enhance quality of life for this group. One way of improving quality of life for these individuals is through sports activities [14]. However, there are many barriers that limit access to such activities, including accessibility, physical limitations, motivation, and limited resources. [12,15,16,25]. Such barriers are more evident for individuals with tetraplegia.

ACM ISBN 978-1-4503-6676-2/19/10...$15.00.
DOI: http://dx.doi.org/10.1145/ 10.1145/3308561.3353775

Figure 1. Tetra-Ski is adaptive skiing equipment.

We developed Tetra-Ski (Figure 1) through an iterative design process to improve access to alpine skiing for individuals with tetraplegia. Tetra-Ski is an adaptive skiing experience that is controlled using a sip-and-puff controller or a joystick. Tetra-Ski has enabled some of our targeted users to ski independently, however it also includes a novel shared-control scheme that enables users to control some aspects of the ski experience, while delegating other aspects to a tethered ski trainer.

Our field study with eight participants and interviews with three trainers at other sites that used Tetra-Ski showed that Tetra-Ski is both usable and enjoyable, that the simulator helped to prepare users for their Tetra-Ski experience, and

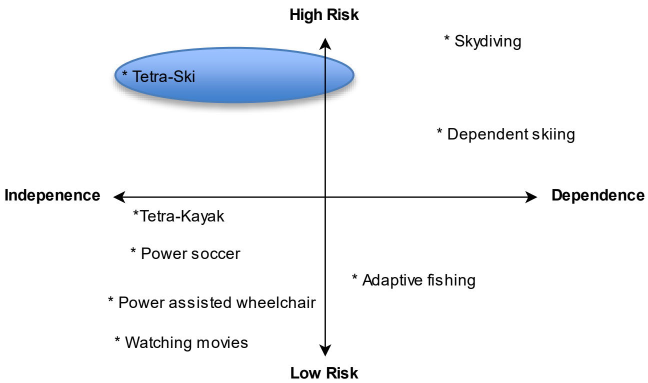

Figure 2. The design space of Tetra-Ski, which enables high-risk, active sport activity and empowers participants to have a range of control over the experience.

that the experience has a positive psychosocial effect on users. The shared-control scheme developed for Tetra-Ski proved crucial for supporting the unique abilities of different users, suggesting that a shared-control approach could enable broader access to more types of outdoor recreation in the future.

BACKGROUND AND RELATED WORK

Adaptive skiing for individuals with lower limb paralysis has existed for decades. Its popularity has created opportunities to be sanctioned as an official Paralympic sport. Unfortunately, there are limited opportunities for winter-sports recreation for individuals with tetraplegia. To the authors' knowledge, no adaptive skiing equipment for individuals with tetraplegia would allow for independent control [23]. For example, the Dualski by Tessier offers a dependent ski experience that is piloted by a tethered skier who controls the turns and the direction for the skier. The aims of the Tetra-Ski project are to extend the accessibility of alpine skiing to individuals with tetraplegia by offering an independent control system (see Figure 2).

Outdoor Activities for Individuals with Tetraplegia

Literature on accessible outdoor recreational activities for individuals with tetraplegia is growing but remains quite limited. Recent work reported on the use of a Sip-and-puff controller for a binary commands system (sip, puff) to offer an independent sailing experience for individuals with tetraplegia [19]. The system enabled participants to successfully navigate a specific course independently. This work provided valuable insights for accessible outdoor recreational activities for individuals with tetraplegia, however no in-depth description of the chosen input system or the development process was offered. With Tetra-Ski we aim to extend the range of usable recreational and sport activities available for individuals with tetraplegia. We also report in-depth on design, users' reactions, and user feedback on the Tetra-Ski experience.

Virtual simulations have been explored to prepare users for real-world adaptive recreation. A pilot study [7], demonstrated that a virtual sailing simulation (VSail-Access) enabled users to better perform the assigned tasks in the real-world. This study also indicated that using the simulator led to salutary psychosocial outcomes, like increased quality of life. This study only included users who can use a joystick, which limits applicability to individuals that use other means to control their assistive technology (e.g. sip-and-puff).

Device	Outdoor	API	Responsive
Joystick	✓	✓	✓
Sip & Puff	✓	✓	✓
EMG Sensors	✓	✓	X
EEG	X	✓	X
Eye Tracker	X	✓	X
Tongue Controller	X	N/A	✓
Quadjoy, Quadstick	✓	X	✓
Tetramouse	✓	X	✓

Table 1. Selection criteria for Tetra-Ski input device: Outdoor – ability of the input system to function in an outdoor environment. API – whether the input device can be integrated with our system. Responsive – if the input device is capable of detecting and reporting commands promptly enough to control the ski in real-time

Input Systems for Individuals with Tetraplegia

The input system for the Tetra-Ski requires special consideration and design innovation to create a usable system for individuals with tetraplegia. We examined multiple inputs system (see Table 1) that have the potential to work with this population. Input systems we examined include: eye trackers, facial recognition systems, EMG wireless sensors, EEG sensors, and a tongue controller [13]. We decided against these systems due to lack of access to the technology (tongue controller), poor outdoor performance (eye trackers, tongue controller, facial recognition systems), or limited accuracy/response time required for highly dynamic systems for activities like skiing (EMG sensors, EGG sensors).

We also considered input control devices from the gaming community. Devices like Quadjoy [5] and QuadStick [18] are examples of adaptive customizable control systems that enable individuals with tetraplegia to play mainstream video games independently. Similar technologies such as TetraMouse [26] and Integra Mouse [10] are designed to simulate the functionality of a mouse. These systems utilize innovative design concepts such as combining two input devices to control a video game (Sip-and-puff controller and mouth joystick), also mapping different commands to different actions in the game with the ability to customize the thresholds of each action. Unfortunately, these are closed systems that have very specific purposes and are not tested for outdoor activity use. Accordingly, these systems could not be used to further the aims of this project.

We initially designed the Tetra-Ski chair with a goal of autonomous piloting by the skier. Shared control was initially conceived of as a way for the tethered skier to perform some of the commands to help control Tetra-Ski for safety. Similar concepts have been explored in the power-assisted wheelchair domain [20,22] with automated commands to enable automation over some control of the wheelchair functions, such as shortcut commands to perform automated actions. Inspiration for the Tetra-Ski shared-control scheme came in part from these examples.

Shared Control Systems for Assistive Technology

Shared-control systems have been explored recently to enable blind participants to participate in outrigger canoe paddling [2]. The control system relies on two participants collaborating to control the outrigger paddling experience. The blind user controls everything in the paddling experience except for turning, which is controlled by another person using a wireless remote controller. We contribute to the growing body of work in this area by analyzing and reporting on the implementation of a shared-control system in the context of extreme sports and with a different population: individuals with tetraplegia.

DESIGN OF THE TETRA-SKI EXPERIENCE

We designed Tetra-Ski iteratively over a five-year period beginning in January 2014. In this paper we present the current iteration as of May 2019.

Formative Design Work

We used the Design Box method [1] over several discrete inductive ideation sessions with the research team, the development team, and medical provider stakeholders (e.g., physician, psychologist, occupational therapist, physical therapist). We gathered additional design input from individuals with SCI/D and individuals with tetraplegia participating in adaptive recreation camps and from patients at hospital locations. Ski trainers and professional skiers, including a gold medal Paralympic skier, contributed to Tetra-Ski's design and the computer-based simulation through conversation and feedback.

Design Goals

Our initial design goals were based on the overarching aim of enabling independent skiing for individuals with tetraplegia, and the results of the design sessions described above. The design goals included:

1. **Safety**. The safety of the skier is essential and the most important criterion. The goal is to minimize additional risk beyond the baseline inherent risk in skiing.
2. **Independent piloting**. It should be possible for a user to operate Tetra-Ski completely independently and with as much autonomy as possible.
3. **Adaptability**. Maximize adjustability to accommodate the diverse needs of users, their abilities, and their wide array of assistive technology.
4. **Diverse user controls**. Since individuals with tetraplegia use a range of control systems, we were committed to expand control options from relying solely on hand-based controls.

Tetra-Ski Hardware

Tetra-Ski is an electrically powered adaptive alpine skiing device. This technology uses actuators to move the skis mounted below the chair. The actuators can be controlled using either a joystick or a mouth input device (SipNPuff).

We designed the Tetra-Ski to enable the parts of the chair that support the arms, neck, feet, and legs of the skier to be adjusted into multiple positions. The goal is to provide the most comfortable seating for the skier and to avoid excess pressure on their body. This level of adjustability is also important due to the nature of our target population; such customization allows the user to hold their body steady while they are performing hard angle maneuvers with Tetra-Ski. Without this support, they would likely find these motions difficult or impossible.

Tetra-Ski Controls

The control scheme for the Tetra-Ski went through multiple iterative developments cycles during the design phase. It is controlled using either a Joystick or a SipNPuff device. These controllers are considered the most common input devices utilized by our target population for controlling power-assisted wheelchairs. The prevalence of these two controllers for everyday activities and their compatibility with a range of technology drove our decision to make them the primary control system options for Tetra-Ski (see Table 1). Other benefits of a Joystick or SipNPuff include easy to access hardware, low cost of production, and durability in extreme environments (i.e. cold).

Following the mapping for power-assisted wheelchairs, users control Tetra-Ski through four main commands: LEFT, RIGHT, UP, and DOWN. The LEFT and RIGHT commands turn Tetra-Ski to the left or the right. The UP and DOWN commands decrease and increase the angle of the wedge of the skis. Decreasing the wedge of the skis increases speed but causes turning to be less responsive because of the design of Tetra-Ski's kinematics, where a lower wedge angle comes with lower range of turning motion. Similarly, increasing the wedge reduces speed and allows for more responsive turning. Different wedge angles are preferred depending on skiing conditions: On a shallow slope, the angle of the skis should be nearly parallel, and on steep terrain the skis should be in a wide wedge to be able to ski safely and to enable more responsive control over turning the Tetra-Ski.

Joystick Controller

The joystick intrinsically maps to the LEFT, RIGHT, UP, and DOWN commands. However, mapping the commands from the joystick to control Tetra-Ski required multiple iterative development cycles. We refined the actuators' response to the joystick, the position of the joystick in relation to the user body, joystick motion dead zones, and response time. Further, we iterated to define a maximum speed for turning and moving to reduce the risk that the Tetra-Ski would flip due to over-aggressive motion.

Command	Wheelchair SipNPuff	SipNPuff V1	SipNPuff V2	SipNPuff V3 [advanced](basic)
Forward (Faster)	Hard puff	Hard puff/ long Puff	LongPuff or PuffPuff **	[short sip cycle through modes]
Backward (Slower)	Hard sip	Hard sip/Long Sip	Long sip or SipSip **	(remote cycle through modes)
Turn Left	Soft sip	Sip	Sip	Continuous sip
Turn Right	Soft puff	Puff	Puff	Continuous puff
Stop Turning/Moving	Hard sip/puff	Single sip/puff	SipPuff	Cease sip/puff

Table 2. Iteration of the sip puff control scheme for Tetra-Ski. ** both commands were tested separately.

Sip and Puff controller

The SipNPuff control scheme presented a more difficult challenge for the research team and the engineers. Skiing is a physically demanding experience that requires continuous response and interaction by the user, and physical abilities associated with our target population add challenges. Further, the respiratory capabilities (which SipNPuff relies on) of a person with tetraplegia can be less than that of someone without tetraplegia. We made a concerted effort to reduce the respiratory burden of engaging the SipNPuff controller to match the user's abilities.

For the first iteration of SipNPuff, the research team looked at the control scheme employed in power assisted wheelchairs for inspiration (see Table 2 second column). Four commands are available for the user of a power-assisted wheelchair: *HardSip, SoftSip, HardPuff*, and *SoftPuff*. The difference between the hard and soft command is based on whether a sip or puff exceeds a certain air pressure threshold. In this scheme, the user does a continuous *SoftSip* or *SoftPuff* for turning left or right. To move backward or forward a single *HardSip* or *HardPuff* starts the movement toward the intended direction, and the opposite command (*HardPuff* or *HardSip*) stops it again.

We designed the SipNPuff V1 control scheme based on this scheme (see Table 2 third column). A single *Sip* or *Puff* would make the skis move all the way to the left or to the right, respectively. To stop the skis at a certain location/position the user follow the turning command (*Sip* or *Puff*) by the same command (another *Sip* or *Puff*). Up and Down commands were triggered by a *HardSip* and *HardPuff* command, which would increase/decrease the ski wedge angle by a predetermined amount (50% and 100% of the maximum wedge). In further iteration we switched from *HardSip/HardPuff* to *LongSip/LongPuff* making the commands time triggered rather than power triggered.

Part of our goal was to provide a fully independent control system, similar to the joystick control. The first challenge we encountered in preliminary testing was low accuracy rates for distinguishing between hard and soft puff commands. We attribute this to the nature of skiing: it is a very demanding sport, which requires the user to switch from one command (e.g. turning left) to another (e.g. turning right) multiple times back and forth in a short period of time. This can be more challenging due to the changing conditions of a ski slope, such as weather and snow conditions. From a safety perspective, there is very little tolerance for error in distinguishing between hard and soft SipNPuff commands. For example, a user might accidentally go faster instead of turning, or turn instead of going slower.

Moving toward a less error-prone design, the research team implemented a sequential binary SipNPuff approach. This approach enables the user to perform very distinguishable commands, which resulted in lower error rates. The team expanded on the "stop turn" command from V1 (*SipPuff*) and added new commands: *SipSip* and *PuffPuff*. In the SipNPuff V2 scheme (see Table 2 fourth column) a *SipSip/LongSip* or *PuffPuff/LongPuff* command increased/decreased the wedge of the skis which affected turning speed and Tetra-Ski max speed. Like in V1, users could turn Tetra-Ski by performing a single *Sip* or *Puff* to turn all the way left or right and a *SipPuff* command would stop the turning of the skis. Also, the new sequential binary system allowed the team to add additional commands such as re-home (which set the skis in neutral position) and full forward (which places the skis in parallel for maximum speed). We performed multiple tests using different mappings of the sip and puff combination in real-world testing and using a computer simulation (see below).

The new system reduced error rates (a reduction in accidentally triggering unintentional commands). However, users were unable to perform more than eight continuous turns using this system in real-world testing because the trainer had to stop Tetra-Ski to avoid going off the edge of the ski run or crashing into other skiers on the slope.

The team determined that these issues appeared related to users' inability to visually locate the current position of the skis. Neck and head movement is often limited in this population, and users cannot look down to visually locate the position of the skis. The user often relied on external cues to initiate the Turn Lock command to stop the skis from turning. This led to early or late triggering of a Turn or Turn Lock command, resulting in unintended steering behavior. These situations resulted in the tethered skier forcibly stopping the Tetra-Ski to avoid danger.

We attempted to improve the experience of using SipNPuff V2 by developing a training platform using a computer simulation (see below) and by enhancing the calibration. These changes led to better performance, but not the

	Mode	Wedge	Turning
Joystick	Basic	*Shared Control via Remote*	Direct Control
	Advanced	Direct control	
SipNPuff	Basic	*Shared Control via Remote*	Continuous Sip/Puff
	Advanced	Sip/Puff cycle mode	

Table 3. Advanced and basic modes for Joystick and SipNPuff controls. In basic mode the wedge of the skis, which controls speed, is handled by the tethered skier using a remote to cycle through modes. The SipNPuff advanced mode enables the Tetra-Ski occupant to control the wedge by cycling through modes. The tethered skier can also take control when necessary for safety.

targeted goal of enabling the users to operate Tetra-Ski for the entirety of the ski run. To solve this problem, we introduce SipNPuff V3 in the next section.

The Frame of Shared Control

The V2 iteration of the SipNPuff control scheme did not perform optimally for our users. At this point in the iteration, we revisited the design goal of using Tetra-Ski independently. We realized that relaxing this constraint would open new possibilities for the design of the control system and would still enable individuals with tetraplegia to control some aspects of their skiing experience.

Our previous design goals described "independent piloting." Here, we added another design goal to relax the constraint of having a completely independent experience:

5. **Shared Control.** It should be possible for a skier to have a complete and successful experience while only controlling part of the ski chair to accommodate a wider range of physical abilities and prior skiing experience.

Table 3 shows the V3 SipNPuff and joystick shared-control scheme. The new system relies on two users operating Tetra-Ski. The main skier (sitting in the Tetra-Ski) is responsible for the turning tasks and guiding the direction of Tetra-Ski. The tethered skier is responsible for ensuring the Tetra-Ski's skis are in the most optimal wedge (speed and turning speed) for the terrain, snow condition, and user performance. We decided how to distribute the control responsibilities with the goal of providing the chair occupant with the most enjoyable experience. We determined that controlling turning maximizes overall feelings of control and independence while using Tetra-Ski.

For the SipNPuff V3 basic mode (see Table 2), a single *Sip* or single *Puff* will move the skis to left or right an amount proportional to the amount of time the user sipped or puffed. Thus, the user has the option to continuously *Sip* or *Puff* for continuous turning. The skis turn at a speed of approximately 6 degrees per second. For the joystick, the user can push the joystick left or right to turn, similar to the previous scheme. We created two modes for the joystick: 1) Joystick basic mode, where the users do not have control over the Up and Down commands and are only responsible for turning commands (left, right), and joystick advanced mode, which is the same as described previously.

The tethered skier is an experienced skier that is tethered to Tetra-Ski using a rope. The main responsibility for the tethered skier is to ensure the safety of the main skier. When in basic mode, they also have the job of determining the wedge for Tetra-Ski based on the terrain, snow conditions, and user performance. The tethered skier has a wireless remote controller designed to be used in a single hand for this purpose. The wireless remote controller consists of a joystick and a button. The joystick is used to:

1. Refine user commands. For example, to complete a turn initiated by the main skier.
2. Take control in an emergency. Used to override main skier commands to avoid hazards or danger.

In addition to using up and down to continuously control the wedge, the tethered skier's remote control button cycles through preprogrammed modes that will place the skis at different wedge angles. A blinking indicator on the wireless remote tells the tethered skier the current mode. Tetra-Ski V3 has four modes that places the ski wedge at approximately 6.4, 12.5, 19.1, and 26 degrees (measured from parallel). This allows the tethered skier to quickly change the ski wedge while primarily focusing on the safety of the chair occupant. The modes are programmed through trial and error by the engineers to accommodate the most common snow and terrain conditions.

Once skiers gain a basic understanding of the controls they can switch to advanced mode. In advanced mode the users are in full control of the four commands. Based on our experience with the significantly challenging task of controlling Tetra-Ski in SipNPuff advanced mode, for this study only joystick users had the option to select advanced mode. In the future, we look forward to making SipNPuff advanced mode an option for users who have prior experience with Tetra-Ski.

In addition to broadening the population of potential skiers, this shared control scheme makes the Tetra-Ski experience more robust to a user's mistakes. This shared control system is also designed with the physical abilities of our participants in mind. Where potential fatigue can occur more frequently for individuals with tetraplegia, shared control allows them to switch between advance mode and basic mode based on their energy level to maximize the time they spend doing the experience.

Tetra-Ski Simulation

As mentioned above, while trying to improve SipNPuff V2, we developed a training simulation (see Figure 3) using Unity3D [27]. The Tetra-Ski simulation is a task-based simulation designed to train users on basic skiing skills before using Tetra-Ski, including turning at the correct time

Figure 3. A level from Tetra-Ski simulation. The UI in the simulation provides the user feedback about which control is being activated. At the same time, visualization of the current position of the skis.

and location and training on the input device and the control scheme before using the real-world Tetra-Ski.

The simulation is designed to match the delays from the real-world hardware in turning and moving, the response delay for the input device, and using real-world elevation data to match the real-world slope terrain. To use the simulation, participants use the same joystick or SipNPuff hardware as with Tetra-Ski.

The simulation is intended to serve several purposes:

1. Train users on the basic skills for using Tetra-Ski.
2. Reduce anxiety for participants.
3. Offer a promotional tool for the experience to reach as many participants as we can.
4. Provide a test platform for users to try new input devices and input schemes.
5. Provide a test platform for developers to try different input schemes and input systems.

USER STUDY

After three rounds of iteration, we wanted to understand how Tetra-Ski performs with a real-world population. The goal of this study was to: (1) measure the usability of Tetra-Ski and the shared control system. (2) Understand users' reactions and feedback. (3) Understand how Tetra-Ski is used when given to other adaptive ski programs.

Participants

We recruited eight participants with the help of the Technology Recreation Access Independence Lifestyle Sports (TRAILS) program. This program ran Tetra-Ski lessons with the participants, and we were present at the ski resort to understand the participants' reactions to Tetra-Ski. We offered the ability to use the simulation during a separate session to all our participants before their scheduled Tetra-Ski experience, but not everyone completed simulation training prior to the real-world experience. For the rest of the paper, we refer to participants who went through the simulation first, and then used Tetra-Ski as group A (6 participants). Group B (2 participants) only used Tetra-Ski and not the simulation.

User (Group)	*Gender*	*Age*	*Diagnosis*	*Wheelchair Control*	*Tetra-Ski Control*
P1 (A)	M	60	Tetraplegia	Feet	SipNPuff Basic mode
P2 (A)	F	20	Tetraplegia	Joystick	Joystick
P3 (A)	M	43	Tetraplegia	Dependent	Joystick Basic mode
P4 (A)	F	48	Tetraplegia	Head switch	SipNPuff Basic mode
P5 (A)	M	50	Tetraplegia	Joystick	Joystick
P6 (B)	F	33	Tetraplegia	Lip controller	SipNPuff Basic mode
P7 (A)	M	26	Tetraplegia	Joystick	Joystick
P8 (B)	M	67	SCI (limited hand motion)	Joystick	Joystick

Table 4. Participant characteristics.

Table 4 show participants characteristics. P3 had very limited communication abilities, so we were only able to ask a few questions during the simulation session. Also, the TRAILS program distributed five Tetra-Ski devices to additional locations around the US to be used by other participants. With the help of the TRAILS program, we interviewed three trainers. We refer to these trainers as T1, T2, and T3. T2 and T3 played the role of the tethered skier at their programs for Tetra-ski.

Study Procedure

All study procedures below took place in the winter of 2019 and were approved by our institution's IRB.

Tetra-Ski

Before each participant's real-world Tetra-Ski session, the research team met each participant at the designated ski resort. We interviewed all participants to understand any concerns before using Tetra-Ski. After the session, we administered questionnaires and conducted a final interview with each participant at the ski resort to gather feedback from the participant and to understand their experience.

At the end of each skiing session, the research team also asked the trainer for observation and feedback about the user's skiing performance and experience. For the trainers from other programs, we collected feedback and observations from the three trainers using phone interviews, focusing on the trainer's overall experience rather than on their individual participants.

Instruments

The team used a mixed of qualitative and quantitative tools in order to capture as rich of a view of the study as possible.

For the simulation, we collected performance data including time to complete the level and how many interactions with the input occurred throughout the session.

We utilized the Psychosocial Impact of Assistive Devices Scale (PIADS) [11] to measure the psychological effect of Tetra-Ski on the participants. We created a 7-item questionnaire to determine how prepared to use Tetra-Ski

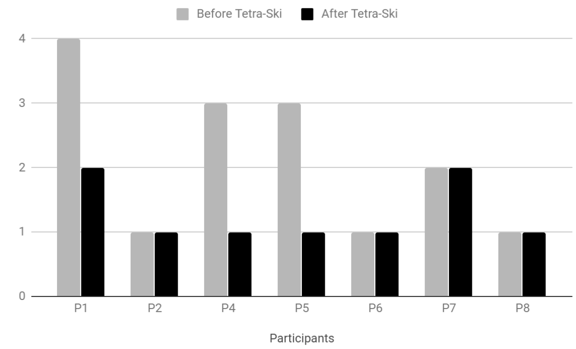

Figure 4. Self-reported anxiety levels before and after Tetra-Ski experience. Points on the scale were labeled: 1 (no anxiety), 4 (moderate anxiety), 7 (very severe anxiety).

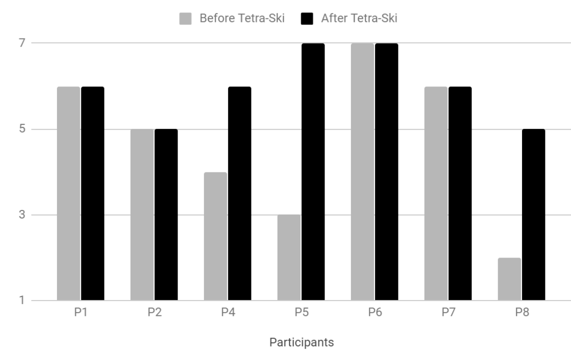

Figure 5. "Feeling prepared" responses from the participants. Values range from: 1 (not feeling prepared) to 7 (feeling very prepared)

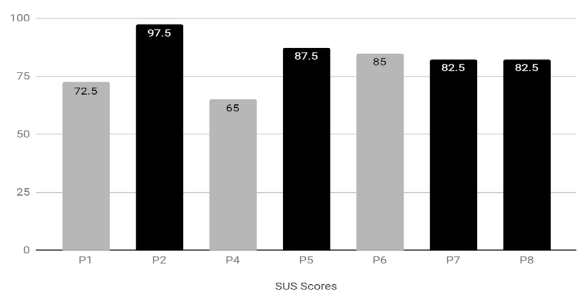

Figure 6. System usability scores after using Tetra-Ski. Grey bars are SipNPuff users. Black bars joystick users. No data reported from P3.

the participant felt. The scale ranges from 1 "not feeling prepared at all", to 7 "feeling very prepared." We used a 7-item scale to measure anxiety [9]. Finally, we used the System Usability Scale (SUS) [6], to measure the usability of Tetra-Ski and we followed this up qualitative questions.

RESULTS

All participants succeeded in using Tetra-Ski to safely complete multiple runs on the ski slopes. All participants reported either the same or a reduced level of anxiety from pre- to post-skiing (see Figure 4) and reported the same or

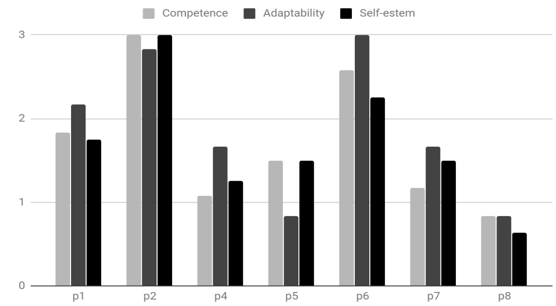

Figure 7. PIADS results after using Tetra-Ski. The full scale is -3 to +3, with positive numbers indicating a positive impact by the assistive technology for each subscale. All results were positive, so the negative side of the scale is not shown here. No data available for P3.

increased level of feeling prepared to use the Tetra-Ski (see Figure 5) after using Tetra-Ski at the exit interview. Figure 6 shows the SUS scores after participants used the Tetra-Ski. Guidelines for interpreting the SUS score state that the average is 68 [21]. All participants scored above the average except for P4 with a score of 65. The lowest scores were from SipNPuff users. Participants' SUS results (except for P4) were within the "good" and "excellent" ranges of the SUS adjective rating scale [3].

Figure 7 shows participants' responses on the PIADS questionnaire. PIADS measures the psychosocial impact of assistive devices. According to the PIADS manual [8], *competence* "measures feelings of competence and efficacy" and *adaptability* "indicates a willingness to try out new things and to take risks." The third subscale, *self-esteem* "indicates feelings of emotional health and happiness." The subscale values range from +3 to -3, where positive numbers indicate a positive change in the subscale.

All participants reported a positive impact on the three sub-scales (competence, adaptability, and self-esteem) after using the simulation and after using Tetra-Ski.

Simulation Trials

All Group A (simulation) participants showed improvement in turning and had better control over Tetra-Ski between the first and final trials of their sessions. Table 5 shows data from participants' simulation sessions. SipNPuff users (P1 and P4) started with lower performance scores and spent more time using the simulation than Joystick users (P5 and P7). Both SipNPuff users asked for another simulation session. P1 was able to come back and do another simulation session, but we were unable to schedule another training session for P4 due to time constraints. P3 was unable to use joystick advanced mode due to his condition and was the only joystick user to use only basic mode. P1 started with using SipNPuff based on the recommendation of TRAILS staff. The simulation data showed that both SipNPuff users (P1 and P4) tended to overperform sipping and puffing to turn in the simulation; they kept engaging the SipNPuff controller even if the skis were already at the maximum turning angle. They explained that they wanted to turn faster or were unsure they had performed the command accurately. P1 in particular reported concerns about the SipNPuff controller being responsive and that he was unable to hold it using his teeth. During his first session he switched to Joystick basic mode. He did a second session and returned to using the SipNPuff controller, which he kept as his control device for Tetra-Ski.

Qualitative Results

Participants enjoyed their Tetra-Ski Experience

After using Tetra-Ski, participants had a lot of positive feedback about their experience: "*Awesome! I will be happy to do it again.*" [P1], "*It's awesome.*" [P2], "*I would not change anything about this experience.*" [P6], "*Cannot think of anything I want to change about this experience.*" [P7]. These participants also reported feeling empowered using the Tetra-Ski: "*I would be interested in using the ski chair again because it gave me a sense of empowerment over my quadriplegia and control over my environment.*" [P6]. P7 described enjoying a sense of control or autonomy: "*I like seeing beautiful things and going kind of fast … [it was] fun being able to choose where I wanted to go.*"

We were unable to collect participant feedback at other sites; however, we interviewed the trainers at three other sites. T3 reported Tetra-Ski was the first time their program could offer independent skiing for individuals with tetraplegia, including individuals with neurodegenerative movement disorders and congenital disorders, like cerebral palsy. T1 and T3 both reported that users were interest in purchasing Tetra-Ski for personal use.

Shared Control helped participants feel safe and enabled trainers to adjust their support

Multiple participants reported that the shared control system helped them feel safe during the experience. They were reassured knowing that the trainer could take control over Tetra-Ski if it was necessary to avoid a dangerous situation: "*The [trainer] was always there to help out.*" [P1], "*The [trainer] helped [me] not get in a lot of wrecks*" [P3]. The idea of shared control came so naturally that many of the participants did not even comment on it directly when we asked them about the control scheme.

While on the mountain, both P5 and P8 switched multiple times between the joystick basic and advance modes. Changes to control mode were made collaboratively between the participant and trainer. The decisions to go between basic and advanced modes were based on participant performance in the current mode. If things were going well in basic mode, they could switch to advanced mode to give it a try. If participants started to experience a decrease in performance, often because of terrain conditions or participant fatigue, they would go back to basic mode. This had the effect of extending the overall on-the-mountain experience because participants had another option when they became fatigued besides simply stopping.

	First trial Score	*First trial Time(s)*	*Final trial Score*	*Final trial Time(s)*	*Total time (min)*	*Total trials*
P1	5/19	IN	16/19	146	56.4	18
*P1**	3/19	IN	11/19	185	56	13
P2	6/19	91.8	14/19	103	19	11
P3	0	IN	7/19	131	9	7
P4	6/19	122	13/19	138	36	8
P5	12/19	120	17/19	135	20	5
P7	12/19	132	18/19	133	17	12

Table 5 Participants simulation results. Scores are based on how many checkpoints (gates) the user crossed. The first trial is the first played session. Final trial is the last played session on the simulation by the participant. IN=user did not reach finish line

The tethered trainer from our program reported that all participants' performance improved with time. In one instance, the trainer saw that P7 was performing very well after the first run. The trainer discussed it with P7 and they agreed they should switch him to joystick advanced mode.

In a different case, P3 has neurological disorder that results a very limited and slow hand motion. The medical staff, trainers, and his experience with the simulation, suggested he would be unable to safely control the ski on his own: the trainer would have to control everything. However, on the slopes, the trainer noted that P3 was able to use Tetra-Ski in joystick basic mode on less steep slopes if the trainer set the wedge to a higher (i.e. slower) setting and left it there.

In the cases above, the trainer was present and able to work with the user to adjust the controls to a setting that worked best for them by shifting control back and forth between the trainer and the user. In other cases, the shared control gave trainers the ability to compensate when the primary user did something they did not mean to do. For example, P4 accidentally triggered sipping or puffing commands because she was on a ventilator, but the trainer was able to catch and fix these mistakes to limit their impact on the overall experience.

T3 liked the wireless remote control for controlling Tetra-Ski, but he emphasized that the control alone is not enough to stop Tetra-Ski in steep terrain and that the rope is still needed. T3 also gave feedback that he wanted a better indicator for knowing what the current wedge mode Tetra-Ski was in while in basic mode.

The turning delay was frustrating

The trainer, T2, and T3 reported that most of the joystick users were not continuing to hold the joystick left or right when turning left or right. Instead, they were pushing joystick left, letting it spring back to neutral and pushing left again. The result of this behavior made the Tetra-Ski unstable and unable to complete a full turn, which required the tethered trainer to stop or take over the control. In these instances, T3 reported that users became confused when the trainer overrode their control. T3 also reported that users would lift their hands off of the joystick when Tetra-Ski did not behave as they thought it should, and they assumed that the tethered trainer would take over and fix it. This was a major concern for the trainer, who was not always prepared for the user to take their hands completely off the controls.

Choosing between Joystick and SipNPuff

Three of our eight participants used SipNPuff, the rest used Joystick. All trainers from the other sites (T1, T2, and T3) reported only having joystick users at their locations. This is somewhat uncommon because it does not represent the broader population of individuals with tetraplegia. This is because these programs do not currently ski with these patients with more complex presentations. T3 reported that people declined to use Tetra-Ski if they had some muscle power that allow them to use a bi-ski (manual adaptive skiing). All trainers reported that learning to control Tetra-Ski was easier and more intuitive for users who already use a joystick with their wheelchair.

LIMITATIONS

Ecological constraints added to challenges in data collection. For example, scheduling depended on weather conditions and participants' health constraints. These practical challenges are common to adaptive sports research but led to a less robust sample than desired. We were unable to collect data in controlled environments. Interviews occurred in ski resorts and led to occasional interruptions. Despite these limitations, we believe that the core findings of this submission are minimally affected by the practical constraints we encountered.

DISCUSSION AND FUTURE WORK

The results of this study have implications for improving Tetra-Ski and wider value for designing control systems. Participants enjoyed their skiing experiences, found the simulation useful in preparing for the real-world ski experience, and improved their performance with practice. The results also revealed several important findings that speak to deeper insights into the world of assistive technology for extreme sports. First, it became evident that users would benefit from more feedback on ski position. Second, seemingly small differences in participants' physical abilities were identified as determinates of Tetra-Ski usage. Finally, the shared-control scheme added notable value to Tetra-Ski.

There is a need for better feedback on system state

Feedback from the trainers using the joystick control system consistently indicated the users were not holding the joystick long enough to perform complete turns. This led to chaotic motions with the joystick in an attempt to make the skis turn faster. The problem seems to be that the position of the skis is not an instantaneous one-to-one match to the joystick movement—the skis turn gradually to prevent the chair from tipping over. For example, moving the joystick all the way left will gradually turn the skis all the way left. Participants described the delay as frustrating. They instead had to rely on other external cues, such as the joystick range of motion, to determine the locations of the skis. In cases when Tetra-Ski does not turn fast enough (due to snow conditions, actuators capabilities, or the imposed delay) they had no feedback that the system has received their joystick command. In these cases, participants re-issued the joystick command to attempt to fix the problem, but the real problem was with the "gulf of evaluation" [17]; participants did not know the command had been received.

While we can imagine opportunities to reduce the time delay through a more complex control system, this represents a significant engineering challenge. In the meantime, one potential solution is to develop a joystick with better haptic feedback with a direct mapping that matches the current state of the skis. Thus, if the user wanted to turn left, they would press left, but the joystick would only move a little bit at a time, corresponding to the delay imposed on the skis. If they let go, it would slowly return the middle neutral position as the skis turn.

The trainer did not report this same issue for the SipNPuff users. However, after examining system logs, we found that SipNPuff users were overperforming sipping or puffing. This is essentially the same behavior as described above with the joystick, but this is more problematic with SipNPuff: 1. it requires abnormal breathing, which can exhaust the user and 2: it is not easily observable by the trainer. This might also explain the comparatively lower SUS scores by SipNPuff users. Again, we believe the issue here is a lack of immediate feedback from the SipNPuff system regarding the location of the skis. This challenge is different from the joystick, because the joystick has visible, proprioceptive, and haptic feedback for the control state (based on the position of the joystick, the user can tell that the command is to turn fully). There is no such feedback from the SipNPuff controller. Training on timing using the simulation led to better results for the SipNPuff users as well as joystick users inside the simulation, but that did not transfer fully to the real-world experience. A major opportunity to improve Tetra-Ski lies in providing better feedback on the state of the skis. One possibility is visual feedback (e.g. using AR glasses to indicate the current position of the skis) or a direct mapping haptic system for the joystick. However, we would like to explore other solutions and modalities (e.g. flags on tips of skis, audio, or haptics) as well.

Accounting for individual physical capabilities

Individuals with tetraplegia have a wide array of presentations and many differences in their physical abilities. During this study, we relied on the medical team care guidelines and recommendations on the physical abilities of the participants. Such recommendations can be generic and do not fully capture the abilities of each individual with tetraplegia. For instance, the medical team described P1 as a SipNPuff user for Tetra-Ski. However, P1 had enough limited hand motion during the simulation trial that he successfully used joystick basic mode to navigate the simulation. P1 had already decided on using SipNPuff for his real-world experience, which is what was recommended based on his diagnosis and medical history. Having access to the simulator gave him a low-stakes opportunity to explore using the joystick.

P3's case further illustrates this point. He has a neurological disorder that limits the range of motion and speed of his hand. The consensus from his simulation results, scores, and the medical team were that P3 would not be able to successfully control Tetra-Ski. However, the trainer indicated that this was not the case on the ski slopes. Instead, P3 was able to independently perform most of the turns on shallower terrain with some help from the tethered trainer. As the Tetra-Ski experience becomes available to more patients, we believe it is necessary to develop a better approach for determining the capabilities of each participant. Even with our small sample size, we found that individuals with tetraplegia have varied and unique presentations. Echoing the basic tenants of ability-based design [28], these differences matter for their Tetra-Ski experience and should be considered.

One possibility for better measurement is to identify minimum performance metrics that include the very basic set of skills and response times. These can be used as a guideline to indicate whether a participant can functionally use the Tetra-Ski. Furthermore, it is possible to explore all options and customization with the participant without any pre-determination about their physical abilities. In the case of P3, the flexibility of Tetra-Ski for supporting various levels of interdependence created a space where he could try controlling Tetra-Ski in the real world, even when nobody thought he would be able to do so successfully [26].

Shared control for enabling access to extreme sports

Initially, we considered the shared-control system a solution to the barriers of using SipNPuff as a control mechanism—SipNPuff alone was not usable and required additional input from the trainer. However, the shared control approach ended up playing a bigger role than just providing a usable SipNPuff control scheme, it enabled the whole range of our participants to have safe and satisfying ski experiences in concert with their physical abilities. Initially, the goal was to provide the user with the feeling of independence and control over the experience by limiting the direct interruptive control by the tethered skier. However, we saw that participants acknowledged and appreciated the role of the trainer in sharing control of Tetra-Ski. Further, contrary to our naïve initial assumption, participants' goal for the experience was often enjoyment rather than independence.

While skiing, participants could (and did) decide with the trainer that they wanted to change the level of control they had over Tetra-Ski and the trainer would adjust their behavior accordingly. The ability to switch between basic mode and advanced mode enabled our participants to enjoy the ski-chair for longer durations because switching to basic mode would offer a relief from fatigue.

Regardless of physical ability, skiing is a difficult skill that can be challenging and frustrating to learn. Frustration can lead novice skiers to quit and feel that they are limited in their abilities. Our team witnessed this with participants in previous iterations of ski-chair design, where the input system was not responsive enough leading participants to quit the experience. By contrast, the shared-control scheme in Tetra-Ski enables beginner users and users with limited physical abilities to ski with a much gentler learning curve.

One shortcoming in the current shared control system is a means for communication between the trainer and the user. Currently, communication while skiing relies on the trainer observing the behavior of the user. This worked in some situations, but as some of the trainers noted it also led to situations where they expected the user to be doing more than they were actually doing and the trainer was caught by surprise. Considering the Tetra-Ski experience through a lens of interdependence [4], we believe more work is necessary to understand and better support the social relation between the user and the trainer moving forward.

CONCLUSION

Designing an independently controllable ski experience for individuals with tetraplegia is an interdisciplinary effort that has both targeted and generalizable implications. Our findings can enhance the design of adaptive ski technology, but also more generally they inform the design of adaptive controls. Aligned with the goals for enhancing autonomy and safety, the shared control input scheme allowed individuals with tetraplegia to control their skiing experience safely with minimum training, which fostered independence and resulted in an enjoyable experience. Future directions include improving feedback and developing a communication system between the participant and the trainer. Addressing the complexities of the shared-control schemes in other contexts has the potential to further broaden access to extreme recreational activities for populations that have traditionally been excluded from them.

ACKNOWLEDGEMENTS

We gratefully thank the TRAILS program for support and help throughout the study. We also thank Tetradapt (https://Tetradapt.us) for allowing us to study and report about Tetra-Ski.

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