Applying Ability-Based Design Principles to Adaptive Outdoor Activities

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ABSTRACT
Effective design is essential to creating adaptive outdoor activities. Ability-Based Design (ABD) is an approach to accessible design in the HCI literature that we found to be most appealing for this endeavour. ABD focuses on making systems adaptable to users' needs and abilities rather than making the user conform to system requirements. We explore principles of ABD in the context of two adaptive outdoor experiences: Tetra-Ski and Tetra-Sail. We found that while the general approach of ABD is useful in this context, some of the basic tenants of ABD can be confounded by: (1) activity risk, (2) dynamic sport environments, and (3) the role of psychological flow during the activity. To accommodate these restrictions on ABD principles and provide a usable experience we developed Shared-Control as a collaborative approach to implementation. This paper explores using Shared-Control and ABD principles in the context of these two adaptive recreation systems for individuals with acquired tetraplegia. This perspective reveals tensions between ABD guidelines and designing for adaptive outdoor activities. We reflect on these tensions, potential additions to ABD, and our own usage of Shared-Control as a mechanism for adhering to ABD principles in this context.

Author Keywords
adaptive sailing; adaptive skiing; ability-based design; adaptive outdoor activities; tetraplegia;

CCS Concepts
•**Human-centered computing** → **Accessibility systems and tools;** *Accessibility technologies;*

INTRODUCTION
Recreational activities have positive effects on physical and mental health-related quality of life for individuals with acquired tetraplegia [6, 37]. Unfortunately, a range of physical and social-contextual barriers to participation reduce opportunities for outdoor recreation. We created the Tetra-Ski [1] and Tetra-Sail [2] to address barriers to participating in outdoor recreation for individuals with acquired tetraplegia. Tetra-Ski is an adaptive skiing experience and Tetra-Sail is an adaptive sailing experience - each designed for individuals with limited range of functioning below their neck. We designed and developed each of these projects iteratively over the course of five years. In this work we examine these projects through the lens of Ability-Based Design (ABD) [43]. ABD emphasizes leveraging user abilities and changing the system to match the user abilities. This approach shifts the burden of accessibility away from the user to technology designers and developers.

However, despite our agreement with the philosophy of ABD, mapping ABD principles to our designs was challenging. A notable hurdle was the environment in which the recreational activities occur. Specifically, the activities take place outdoors in dynamic, fast-paced, safety-critical, hard to predict environments. Accordingly there is a tension between tasks imposed by the requirements of the activity and the environment. This level of risk associated with factors, like weather and terrain, affected how well ABD principles applied.

To address these environmental factors and maintain faithfulness to the principles of ABD, we developed an approach of Shared-Control. In this context, Shared-Control was defined as a collaboration between a control partner (an instructor experienced in skiing or sailing) with the main user (individual with tetraplegia engaging in the activity) to enhance successful operation of the Tetra-Ski or Tetra-Sail. This resulted in greater adherence to ABD principles, while addressing contextual demands of these activities.

The current prototypes of Tetra-Ski and Tetra-Sail were deployed in the Winter of 2018/2019 and Summer of 2019 with eight and nine participants respectively [1, 2]. In both studies participants found these prototypes to be usable, enjoyable, and empowering. Participants also described positive psychosocial effects after using the prototypes. We believe ABD principles, the Shared-Control scheme, and integration of motivation theory played a crucial role in the success of these prototypes to match our users' needs and support their self-directed performance.

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(a) A joystick participant using Tetra-Ski with a control partner tethered to the back of Tetra-Ski. Photo Credit Lee Cohen.

(b) Sip-and-puff Tetra-Sail user with medical staff on the right and the control partner on the left. Courtesy of Deseret News Publishing Company (Credits holder).

Figure 1: Tetra-Sport experiences. On the left Tetra-Ski(a), on the right Tetra-Sail (b).

BACKGROUND AND RELATED WORK

Individuals with Tetraplegia

Tetraplegia, also known as quadriplegia, is paralysis caused by injury or disorder resulting in the partial or total loss of use of all four limbs and torso [42]. In this paper, we focus on acquired tetraplegia, which is distinct from non-traumatic tetraplegia that can be caused by hereditary conditions, infectious agents, and disease. In addition to medical barriers, individuals with tetraplegia encounter notable social barriers that prevent engagement in activities. This in particular relates to whether technology facilitates or hinders participation [22]. Design of adaptive recreation technology must be considerate of medical factors, but also has responsibility of overcoming social and environmental barriers to participation. In the case of recreation technology, the question of social barriers is often, "who was this made for?" Presently, it was clear that opportunities were afforded for non-disabled individuals to engage in skiing and sailing through safety-enhancing technology. Accordingly, we were careful to consider both medical and social factors while designing for individuals with tetraplegia.

Design under the Biopsychosocial Model of Disability

The World Health Organization ICF Biopsychosocial Model of Disability provides a framework for conceptualizing the barriers associated with the medical and social models of disability [21]. This framework is especially pertinent for designing technology addressing adaptive recreation needs. For example, the medical model of disability speaks to how the complexity of an injury can create barriers to participation. Within the design sphere, this is illustrated when injury-related features can be addressed with medical technology to enhance participation. For the present study, our design was considerate of features such as impaired respiration and mobility due to paralysis. Further, a range of social factors also prevent opportunities for participation. These are best described as external and contextual factors derived from political values that create disabling conditions or contexts for the individual with a medical condition. In the case of adaptive recreation, this is illustrated by sport equipment or facilities designed for use by individuals without medical conditions. In the present work, we observed a gap in equity to engage in ski and sailing recreation due to a lack of appropriate and inclusive design. The ICF Biopsychosocial framework integrates these models to offer a more robust view of disability. With regard to design, this framework allows for giving equal weight to needs associated with physical and social restrictions to activity.

Outdoor activities for individuals with tetraplegia

Although social barriers to participation in outdoor recreation are common for individuals with tetraplegia, more opportunities are developing. For example, Accessdinghy [33] have created a commercially available sailing boat that can be outfitted with sip-and-puff or joystick controls. This technology is described as functional with positive effects on the user, such as improvement in self-worth, community belonging, and level of motivation to use the system again [28]. In addition to sailing, multiple commercial offerings exist for skiing experiences, such as Bi-Ski [35], Sit-ski [36], Dual-Ski [17] and TEMPO DUO [38]. A major constraint with these skiing technologies are the limited independence in control over the skiing equipment, especially for participants with complex injuries. Finally, there is a growing community with commercial support for individuals with tetraplegia to outfit their wheelchair to perform outdoor activities such as off-road driving [40], hunting and fishing.

Our work contributes to this literature by describing our design process, use of ABD principles, description of a Shared-Control scheme, integration of SDT principles, and report of users feedback on their use of Tetra-Ski and Tetra-Sail. Often these ski technologies only offer fully dependant experiences, in which the user has no or highly limited opportunities to pilot the experience. We address this limitation by implementing control systems for these users and by applying principles from Self-Determination Theory in our design of the Shared-Control system to promote a greater sense of autonomy and control over the main user’s experience.

Ability-Based Design

The present work is centered on principles and concepts of ABD [43], which focuses on the user's abilities rather than inability. In comparison to other design platforms such as, universal design [18], and inclusive design [25] we favored ABD as it focuses on maximizing utilization for a specific targeted population. This goal has value as it limits the amount of generalization designers need to make about users' abilities and performance. We anticipate this would result in a better match of the system requirements to the user's specific needs and abilities. This targeted approach is critical to successfully perform our highly physical sport activities.

Using an ABD approach also has value in addressing environmental barriers to technology use and participation, such as weather or terrain. These "situational impairments," are contextual determinants that limit use of the technology for users and provide roadblocks for design and development. [16, 20, 34, 39]. This consideration was important to the design of the Tetra-Ski and Tetra-Sail due to the range of environmental barriers to access and performance of the activity. ABD addresses these barriers to participation by shifting the burden of adaptation from the user (adapting to an inflexible system) to the system (adapting to the needs of the user), thus making the experience more accessible.

ABD principles have been applied in many accessible systems, including: SUPPLE mouse pointing solution for users with motor impairments) [19], Smart Touch (a touch screen solution for users with motor impairments) [26] and PLAY-ABLE (a series of interactive physical games for kids with complex motor disabilities) [41]. However, we have not yet come across work that applies ABD principles outside of the context of traditional screen-based experiences. In this work, we apply ABD principles to two screenless, outdoor, physical activity contexts. In doing this, we extend the growing body of work on ABD to include active outdoor physical activities.

Shared-Control Systems

Shared-Control systems have been explored to enable a person who is visually impaired to participate in outrigger canoe paddling [3]. The control system relies on two participants collaborating to control the outrigger paddling experience. The individual with visual impairment controls everything in the paddling experience except for turning, which is controlled by another person using a wireless remote controller. Shared-Control schemes have also been explored as a solution to allow individuals with tetraplegia to perform skiing independently [1]. We contribute to the growing body of work in this area by sharing our design decisions and participant feedback in the context of implementing Shared-Control for sailing and skiing. Our technology design included influence from rehabilitation psychology, drawing from theories of flow states and motivation. In addition, connect Shared-Control ABD concepts.

Design Components based on Psychological Principles

Adaptive recreation technology design requires an interdisciplinary approach. When designing adaptive recreation technology, we included input from a range of rehabilitation disciplines (e.g., physiatry, physical therapy, occupational therapy). In particular there is notable value in including rehabilitation psychology in the design of adaptive recreation technology. Rehabilitation psychology offers theory- and evidence-based rationale for design decisions about behavior, cognition, emotion, performance, and the ontological aspects of lived experiences. With regard to the present project, we paid particular attention to psychological concepts of flow and motivation.

Flow: Optimal experience

The primary goal for Tetra-Ski and Tetra-Sail was to enhance recreation. Further, a major design goal of recreational experiences is to be enjoyable. When designing this technology we accounted for principles of flow theory to increase the pleasurable aspects of the experience [9].

Past work has expanded on this to create the experience fluctuation model [15]. This model describes the different psychological stages associated with performing an activity. These are presented as challenges versus the skills the user previously had or acquires over time. Benefits of flow are numerous, and include improved performance, expedited mastery of skills, and heightened enjoyment [8]. To provide the most optimal experience for the participant, we sought to incorporate basic flow principles in the design, and also incorporated aspects of challenge and skill to ensure Tetra-Ski and Tetra-Sail were enjoyable experiences. These principles were tied to ABD goals of designing to the user's qualities, such as matching the user's ability.

Motivation: Design to support basic psychological needs

Self-determination Theory (SDT) is a leading motivation macrotheory with a substantial body of literature defining elements that facilitate self-motivated behavior [13, 11, 14]. Due to its extensive base of evidence, SDT principles are widely adopted in a range of in-person and digital health behavior change interventions [13, 11, 5, 23]. A cornerstone to SDT is the concept of basic psychological need fulfillment [27, 30, 7]. This microtheory of SDT describes how fulfillment of basic psychological needs (e.g., autonomy, competence, relatedness) develops and maintains intrinsic motivation and self-directed behavior[12, 29, 31, 10]. Autonomy is described as the need for self-directed choice, competence is the need for mastery, and relatedness is the need for positive interpersonal connection. Since the inclusion of control partners has the potential to be demotivating, we determined that Shared-Control systems require support for enhancing self-directed and intrinsically motivated end-user behavior. Accordingly, each of these principles are key for the design of Shared-Control systems. Although this design approach was done for the benefit of the Tetra-Sail and Tetra-Ski users, we believe the consideration of SDT's principles has wider implications for Shared-Control and ABD. We describe this further in the discussion below.

DESIGN PROCESS

The design process of Tetra-Sail and Tetra-Ski has been ongoing since 2015. The design team followed a user-centered design approach from the beginning. Accordingly, the design process included engaging a range of key stakeholders. Initial design goals and targets for the experience were informed by representatives from the TRAILS adaptive sport program at the University of Utah. TRAILS provides access to a wide range of sport activities to many individuals with tetraplegia. During the different stages of iterative development and deployment we gathered data informally from participants (typically individuals with acquired tetraplegia). As various individuals and groups within our team developed different parts of the technology over time, we ensured quality through reviews by stakeholders, including the medical rehabilitation team. For example a mechanical engineering team developed the hardware and electrical controls for both experiences. A game engineering team worked on creating training simulations. As a result, both Tetra-Ski and Tetra-Sail were the result of multiple interdisciplinary teams working and developing theses technologies.

Applying ABD in Tetra-Sport

During five years of iterative development and testing with many participants, we settled on the idea of Shared-Control for both systems as a design strategy. Shared-Control relies on two parties controlling the same activity. In our systems, we have a main user (typically a participant with motor disability) and a control partner (up until now, an experienced adaptive sport instructor in skiing or sailing).

Table 1 shows how both of our systems use Shared-Control to accommodated ABD principles. In the following section we discuss these implementation decisions in more detail.

Adaptation using Shared-Control

We aimed to achieve adaptation in Tetra-Ski and Tetra-Sail using several strategies. First, both experiences provide two modes of operation to accommodate different skill levels. Basic mode for Tetra-Ski only requires the user to control turning, and basic mode for Tetra-Sail users only relies on motor power. Advanced mode adds additional capabilities, including the ability to adjust the ski wedge angle in Tetra-Ski, and the ability to use wind power to propel the Tetra-Sail. The other main source of adaptation is the human control partner, who enables basic mode in Tetra-Ski by adjusting the ski wedge for the user. In both experiences, the control partner uses the remote control to refine users' control actions to adapt to their needs and performance in-situ (more on this below). The control partner also adapts to the user's performance by changing aspects of the experience (i.e, skiing on a steep slope, sailing using motor power at very slow speed).

Using Shared-Control requires an effective communication channel between the control partner and the participant. Based on their observation of participants' performance and communication, the control partner can adjust the system to respond to the participants' abilities and level of experience. We supported this in our design by integrating a wireless remote control that a control partner can use to adjust the system in its various functions (speed, turning speed, number of commands, basic or advance mode, etc.) with minimal effort at any given moment during the experience.

This design focused on providing the most effective communication channel based on the context of the experience. Common communication themes included performance-related concerns, requests, and descriptions of the main-user's expectations. We rely on verbal communication as the main communication method between participants and the control partner. The control partner will use adaptive guidance in their verbal communication with the main user based on their level of experience. In this situation, the control partner provides step by step instructions to perform certain actions. For more experienced users, the control partner will communicate using general terms to assist in the experience. Such communication goes both ways, where the main user can communicate their requests verbally to the control partner using any terms or language they are familiar with based on their level of experience with skiing and sailing. For example an inexperienced main user skier can ask for "more speed" the control partner will adapt Tetra-Ski wedges angles to accommodate the main user's request.

Performance using Shared-Control

When designing the ski and sail control system, we determined that the control partner should help define the appropriate changes/modifications in the system to match user's performance. The control partner adjusts the system based on both explicit (e.g., the user requests to stop the experience because he/she is tired) and implicit (e.g. the user's current performance) feedback from the user.

These factors are dynamic and difficult to determine using an automated system. Accordingly, we continue to rely on the judgement of the control partner, who adjusts the system to match the user's performance. The control partner does this by switching users between basic and advance mode. Another way is by changing the goals and targets for the experience (e.g., using only motor power to sail rather than encouraging wind power or going to a less steep slope). An additional mechanism for adjusting to the user's performance is by changing the level of instruction and feedback given to the users (e.g., full instructions on how and when to turn versus just giving the instruction to turn).

Transparency using Shared-Control

Transparency was an important design feature. Both the ski and sail experiences operate in dynamic environments in which the main user and the control partner benefit from clear and transparent communication. This communication is often conducted quickly due to contextual demands. To accommodate for time sensitivity, the control partners adapt the complexity of the communication, such as changing the level of details about the current system status based on the main user's performance. When using the Tetra-Ski, information is communicated about the operating mode (e.g., basic, advanced), and what the main user should expect while operating the experience in the stated mode. We observed, over time, that the control partners would adapt their communication to shorter utterances, such as only communicating the mode number rather than offering greater detail. We refer to this as adaptive guidance, in which control partners provided users a level of transparency that matched the needs of the user, and what would be useful to share in the moment and context.

Principles	Tetra-Ski	Tetra-Sail
Ability	Many tetraplegic users are able to breathe and/or have limited hand movement and are able to perform basic communication (i.e confirming and responding) and cognitive processing. Individual presentations can differ considerably.	
Accountability	In the Shared-Control scheme, it is the job of the control partner to accommodate the user’s ability and performance. The design was developed with a "stance of accountability" towards individuals with tetraplegia.	
Availability	Tetra-Ski is a modified adaptive ski frame commercially available. Tetra-Ski has been distributed to at least seven adaptive sports programs around the country.	Tetra-Sail is a modified commercially available sailing tandem from Hobie. The TRAILS program hosts a summer sailing camp each summer free of charge for all participants.
Adaptation	Tetra-Ski has basic and advanced modes for users. The control partner refines user actions and controls when needed.	Tetra-Sail users can sail using motor or wind power. The control partner refines user actions and controls when needed.
Transparency	The control partner communicate the necessary system information for the main user and handle user requests to adjust systems when it possible and feasible.	
Performance	Tetra-Ski has both basic and advanced modes. Choose the most suitable terrain (slope) based on the user performance.	Control partner using Shared-Control adapts to user performance by performing actions the main user cannot perform.
Context	Control partner through the use of Shared-Control will sense the environment and place Tetra-Ski in the optimal settings. Based on context, the control partner will change the goals and targets for the experience (i.e., less steep or less crowded slope).	A control partner through the use of Shared-Control will sense weather condition and obstacles in the environment and place sail in the most optimal position, and avoid obstacles for the main user.

Table 1: How Tetra-Ski and Tetra-Sail designs address ABD principles

Accounting for Context using Shared-Control

In both experiences, the control partner acts as a sensor for understanding the environment and the contextual factors affecting the experience, and making appropriate adjustments in response. One way that the control partner does this is by determining the appropriate settings for participants in basic modes (placing skis in the optimal wedge mode based on the environmental context or furling/unfurling the sail in response to the wind). In all modes, the control partner can detect aspects of the environmental context, including terrain (i.e. water choppiness, steepness and snow conditions), weather conditions (i.e, cold, precipitation, wind speed), and identifying obstacles and other traffic. The control partner can then work with the participant to act on this information by communicating it to the participant or by acting directly based on the nature of the situation.

Inclusion of Self-determination Principles

Consideration for facilitating the participants basic psychological needs was included throughout the design, but had particular influence on aspects of the Shared-Control scheme. Enhancing autonomy - the need to choose and self-direct - was a foremost consideration. Although ABD approaches have changed adaptive recreation technology design, this area of design has an unfortunate history of being informed by the medical model. This has led to user experiences being predetermined for the individual rather than enhancing opportunities to choose how to use the technology. With the inclusion of a control partner, we were especially sensitive to creating options for the main user. In this case a range of control levels were designed. Feedback demonstrated participant appreciation for the opportunities for greater self-determined technology use. In line with many sport activities, an emphasis was placed on competence. Individuals are rarely intrinsically motivated to participate in an activity that prevents satisfactory performance. Designing degrees of difficulty satisfied this need for appropriate challenge. With regard to relatedness, a Shared-Control scheme inherently creates a social collaboration. Our design goals were to allow for a mutual experience for the main user and control-partner. This satisfied the need for the collaboration to be cooperative in nature. Further, we discovered interest in widening the control partner from expert instructors to informal control partners, like family members. This indicated the importance of relatedness within the design approach.

CHALLENGES TO APPLYING ABD PRINCIPLES IN OUTDOOR ACTIVITIES

Our initial design sought consistency with the ABD goal for independent interactions with the technology. Accordingly, we aimed for fully independent sail and ski experiences for our participants. However, we faced many challenges in attempting to achieve this design goal:

1. Sport activities (including Tetra-Ski and Tetra-Sail) require a certain amount of training to obtain the skill set necessary for participants to perform the sport independently.

2. Our participants have complex health conditions that require monitoring (i.e., participant unable to breath normally) while performing the sport activity to avoid any life threatening situations.

3. The environment (context) of where our sport activities take place are dynamic and hard to predict due to changing weather and terrain conditions (e.g., snow, water activity). This creates scenarios that the team could not account for in the system design.

4. A major goal was to create accommodating sport hardware that participants with different physical abilities would be able to use (access) without any major modifications or customization. This allows for multiple participants to use our system in the same day without long delays. In order to achieve this goal we had to limit variation of a control scheme to only two input systems (sip and puff, joystick).

5. It was impossible to anticipate the situational impairments that would arise during these experiences without actually trying out these experiences with participants, and thus we could not design for them ahead of time.

Due to these challenges we pivoted the design to include the Shared-Control scheme. This was considered necessary despite the violation of ABD's primary goal of independence. Although this deviation steered the design closer to creating a meaningful technology solution for the user, a few barriers remained. Specifically, Shared-Control and outdoor activities imposed restrictions on how to implement ABD.

Preserving Flow

A major factor of performance and enjoyment in sport activities is creating a level of challenge congruent to the participants' skill level. When designing the Tetra-Sail and Tetra-Ski, we sought to balance creating usable technology, while preserving a level of challenge to maintain flow. For example, creating a fully autonomous experience would not be desirable due to barriers for successful operation. Nor did we want to recreate a fully-dependant skiing experience where the participant's role is completely passive. This led us to create multiple control levels to allow for variation of difficulty. Feedback from the participants indicated our users appreciated having a dimension of challenge to overcome rather than having the experience be as simple to control as possible.

Challenges Implementing Adaptation

We found the principle of adaptation particularly difficult in this context. First, multiple sip-and-puff users asked for their main wheelchair input device (e.g., a head-switch) to be used as the controller for their experience. We considered this in the design, however the team was unable to integrate a usable head-switch interaction due to the notable movement and shaking that occurs while using Tetra-Ski and Tetra-Sail. In general our consideration for the input device was constrained by the outdoor environment and different weather conditions.

This was further strained by our design goal of accommodating all types of physical abilities. This can be challenging to achieve in a real-world deployment. For example, we had one Tetra-Sail or Tetra-Ski. To maximize access, multiple participants were scheduled to participate in the experience each day. Each participant has different needs in terms of the input system, seating requirements, and transfer needs. In addition, we had to mirror the adaptations a participant might have made to their wheelchair. Achieving optimal adaptation for all of these requirements meant increasing the wait time for each participant before the experience and decreasing the amount of time the sail or ski device was being used.

There is a tension between this goal of accommodating all types of physical ability needs and the constraint that each participant only has a few hours to spend using the experience. We wanted to maximize the proportion of time that is spent doing the activity. Thus, Tetra-Ski and Tetra-Sail have a general input system that accommodates many users' needs - but it does not achieve the optimal adaptation for each individual. Similarly, our seating system needed to be adjusted and customized to prevent seating from limiting the view for some of our participants. In general, the design of Tetra-Ski and Tetra-Sail requires the user to conform to it in certain ways (violating ABD's adaptation principle) in order to provide more universal access and reduce setup time for them.

These limitations also affected the amount of adaptation we supported with the input commands. The main user and the control partner are bound by human responses to challenging tasks. To make our systems usable in the context of fast-paced activities like skiing or sailing, there was a need to design for simplicity over fidelity in the control and system interfaces. This required us to reduce the amount of customization and options available to the main user and the control partner for obtaining the best adaptation of the system.

One other unexpected barrier to achieving adaptation was participants' rejection of input devices more commonly used by higher level injury patients. For example, some participants would initially reject using the recommended combination of joystick and sip-and-puff input devices in favor of a joystick-only approach. Instructors found that their recommendation for inclusion of sip-and-puff was accepted after multiple runs of trial and error.

Sacrificing Transparency and Performance for Safety

A transparent interface for our users was deemed an important factor in creating a usable interface. However, in our system design we limited our user customization options to a predefined set of options because certain users choices might lead to very serious harmful situations. For example, a user might override the speed limits on Tetra-Ski, which could increase the chances that Tetra-Ski flips over while turning.

Shared-Control was a must for our systems. It helped our users to use our systems and to ensure safety. However, it also means that the user performance is be dependant on the control partner performance. This might lead to performance throttling by the control partner to ensure safety. Control partners have ultimate power to override users' actions and adaptations for what they believe is best for the experience (e.g., user placing Tetra-Ski or Tetra-Sail at max speed a control partner override that options for safety concerns).

The Importance of Context

We found that environmental demands for outdoor experiences were major factors in designing the system. For Tetra-Ski and Tetra-Sail, shifting terrain and weather contexts constrained how we could achieve adaptation (i.e., input systems a user can use or select), transparency (i.e., users can change speed settings for Tetra-Ski to avoid risk of flipping), and performance (i.e., limited turning speed and capped max speed for Tetra-Ski). This was interesting because it caused us to make compromises on adhering to the other ABD principles in order to accommodate the principle of context.

REFLECTING ON DESIGN DECISIONS WITH PRIMARY TETRA-SPORT DESIGNERS IN THE CONTEXT OF ABD

Other papers report on the user experience of our participant population. Most recently, we conducted two studies, one with Tetra-Ski (eight participants) [1] and one with Tetra-Sail (nine participants) [2] during Winter 2018/2019 and Summer 2019. Though there is some nuance to those results, the high-level takeaway is that participants were able to control Tetra-Ski and Tetra-Sail, and they greatly enjoyed their experiences.

In this section, we report on interviews that the research team conducted with the two main system designers (Designer1 and Designer2) for Tetra-Ski and Tetra-Sail to better understand their design decisions with respect to ABD principles. Designer1 is a medical director of SCI/D medicine at a large rehabilitation hospital, and has over 30 years working clinically and directing a large adaptive recreation program. Designer2 also servered as our control partner for many of our users for both experiences. These interviews were conducted in January 2020. Designer2 is a mechanical engineer who also has over 20 years of professional and recreational experience in skiing and sailing.

We focused the questions in these interviews on the iterative process of designing, implementing, and testing Tetra-Ski and Tetra-Sail. We asked about the design priorities, especially focusing on usability, supporting fully independent control, and safety. For Designer1 we focused more on the bigger picture of the experience and also Designer1's perspective as a physician and also a control partner and with Designer2 we focused especially on technical constraints.

We transcribed the audio recordings from these interviews. One author then went through multiple iterations of reading and processing the transcripts to increase fidelity of the interpretations. A general inductive approach was used to generate codes and themes, focusing in particular on the relationship between our design process and ABD.

Safety is the highest priority for designers

Both designers identified safety as the highest priority in their design decisions:

> *"The biggest things that concern me about both of these devices is is safety. You know, the people that have been injured in the past don't think that they can be more injured, but I know that they can be. I mean, both with the ski and the sail [we have to be careful]. You know, being out of control and capsizing and drowning. ... While we still improve performance and independence, we can't ever forget, you know that things could go wrong quickly and we have to design for that."* [Designer1].

> *"it's not quite as high performance as it could be, because we don't want to risk getting into an unsafe situation and for both devices, that unsafe situation is probably flipping over."....* *"I mean, in general, like I would like both of them to be a little more high performance. And I think that's probably coming in the next iteration. But we do have to maintain a safe experience."* [Designer2].

Both designers identify that to maintain a safe experience for the participants, they have to trade off other qualities that they would also like to prioritize including performance and independence. Ultimately, for these experiences safety must come first.

Shared-Control enabled a safer and more independent experience for participants

Both Designers reported that Shared-Control has been a necessary step to allow participants to learn skiing and sailing without disruptive interference:

> *"I think no matter how independent people get, when we're dealing with folks that that have this level of disability, there's always some degree of, you know, maybe not dependence, but you know, collaboration is always going to be another person to work with to some degree."* [Designer1].

> *".... And so the [Shared-Control] has significantly transformed how we teach and also how we we make judgment calls when a safety situation or you know, a dangerous situation might come up."* [Designer2].

While a fully independent experience still seems to be infeasible from a safety perspective, Shared-Control has enabled an experience that is closer to an independent experience.

Designers' primary goals were independence and high performance

As mentioned above, both designers were aiming for fully independent skiing and sailing experiences for this population. Although the design goals aimed for experiences that match our targeted population's physical abilities, the designers were dedicated to not compromising performance and independence-focused control features:

> *"two things in design, in both of them were to give as many features ... of these devices needed to be independent, but then also offer high performance and so I didn't want any compromise".* [Designer1]

Although salutary, the designs ended up compromising on these goals for a variety of reasons - as discussed in this manuscript, chiefly safety.

Challenges of being in a deployed, uncontrolled setting

Designer1, a medical doctor and adaptive trainer for many years, recognized a range of challenges for the participants:

> *"many of these patients have not done sports and activities and things like this before. And we're asking them to do something that they haven't done before, and then work with a control system they haven't used before. And these are often people that don't get out very much".* [Designer1]

Because of this, it can be difficult to anticipate a particular participant's abilities until they are already having the experience:

> *"So there's some situations particularly with the ski, where we knew that people [have limited hand and body motion and strength], let's say in their shoulders or their neck and their head, but it was hard to tell in an environment where they were just in their chairs because it wasn't a very dynamic environment. So once we put people in the ski, they started being very independent and and doing a lot of exciting things,[When participants try our adaptive sport] some [and unexpected] limitations came out that we didn't know before!".* [Designer1]

In the example given above, the participant's abilities are different in a positive way once they are in the experience. However, this same mechanism can also mean that participants have a disappointing outcome:

> *"oftentimes that first experience that you want to be very special for them is just nerve wracking and frustrating. And that’s hard when people expect to have the experience of their lives. And it really ends up being just a tease because they can’t do it to the way that you designed it that that that’s frustrating".* [Designer1]

Perhaps part of the challenge here is that participants’ control experiences all come from controlling their own wheelchair, but the context and the physics of controlling a ski or sailboat are sufficiently different:

> *"The other major limiting factors are the, the instability and like the jostling and the G forces involved in ski are a lot higher than a wheelchair. So something like a chin joystick or an eye tracker, you know, some of some of the other common wheelchair control devices out there wouldn’t work for the ski just because it’s too bumpy and people are getting pulled around. They don’t have that fine motor control to actually use those devices."* [Designer2]

This imposes other limits on the design, for example limiting designers’ ability to accomplish adaptation because the input device won’t work in this context.

> *"I think that it’s hard for us without a disability to appreciate the lack of input their body is getting, like I think when an able bodied person skis and a puffer sip, there’s so many parts of their body that are feeling changes, you know, they’re feeling the change of gravity, or they’re, you know, they can feel their bottom and feel how pressure is changing very subtly. And so they get this, this feedback and our other folks that can’t perhaps feel anything or move anything below their neck. There, they’re just they need more input.* [Designer1]

As Designer1 highlights here, it really is impossible to understand what it feels like for individuals with tetraplegia to be using these systems, but we can be confident that it is different from the experience that a typical individual without tetraplegia would have.

DISCUSSION

Reflecting on the design process and constraints of developing Tetra-Ski and Tetra-Sail in the context of ABD principles helped us to surface the challenges of applying ABD principles in designing outdoor adaptive recreation technology. The results revealed several important findings regarding implementing ABD principles in technology-mediated adaptive outdoor activities. First, safety is an important addition to the principles necessary for this context. Second, there is a tension between achieving adaptability and having the user engaged in performing an outdoor activity. Finally, Shared-Control notably contributed to successfully applying ABD in both Tetra-Ski and Tetra-Sail. We believe these findings also apply more broadly to designing other adaptive outdoor activities.

Extending ABD for outdoor activities

During our deployment process for Tetra-Sail and Tetra-Ski, we faced many challenges that limited our ability to apply ABD principles based on the design recommendations from [43]. We attribute the main factors of such challenges in the amount of **risk** involved in the activity for the participant and the **context** of the experience. Both of these factors have an impact on the safety of the participant, which is not a part of the ABD framework, but is an essential priority in our designs. Our implementation of Shared-Control helped to address these issues. Shared-Control provided an extra layer of fail-safes for the control partner to ensure safety.

Shared-Control also helped us to discover situational factors that affected the abilities of our participants which the medical staff or engineers had not been able to anticipate. Medical staff and the engineering team explained that this was due to the nature of developing new interactions in new contexts that had not been extensively studied before or reported for our population. As a result, the team made all of the design decisions based on the best information we had available to us, primarily user behavior using a wheelchair system, which did not translate to our outdoor experiences. Only once we deployed these systems were we able to understand the impact that these new situations had on our participants (often individual differences). This would have effectively been a chicken-and-egg problem had it not been for our ability to deploy these systems using Shared-Control.

Based on our experience with Tetra-Sail and Tetra-Ski, one major recommendation we have extending ABD to include adaptive outdoor activities is to have *Health and Safety* be a required principle. Taking a broader view of the contexts and populations to which ABD might be applied, we believe that it is especially important in the context of designing for all abilities to consider the ways in which a design can affect the health and safety of the user. For us, safety was an absolutely required principle.

This leads us to the other change that we would propose when applying ABD: that prioritizing the principles in the context of a particular project is an important step. For example, for our first iteration we focused on creating a usable input system and control scheme for both Tetra-Ski and Tetra-Sail. Thus, in that round we prioritized *adaptation* (see Figure 2). While we acknowledged the importance of context initially and in retrospect it seems obvious, it was not the primary focus in our initial iteration. Next came performance, in large part because we though that optimizing for performance would maximize enjoyment (consistent with Flow Theory). Finally, transparency seemed least important of these principles.

After the first deployment we learned a lot that we were not previously aware of. The Tetra-Ski context presented many challenges for our participants in terms of controlling Tetra-Ski or supporting their bodies to handle the different context conditions.As a result, context raised to the top of our priority list for Tetra-Ski. For Tetra-Sail, we found using the modified Mirage Hobie Island craft provided our users a higher level of safety, which led us to focus more on designing a more enjoyable experience and to support more independence. In this situation, adaptation and performance rose to top of our list. Through this process, prioritizing and reprioritizing objectives was an important part of our design process.

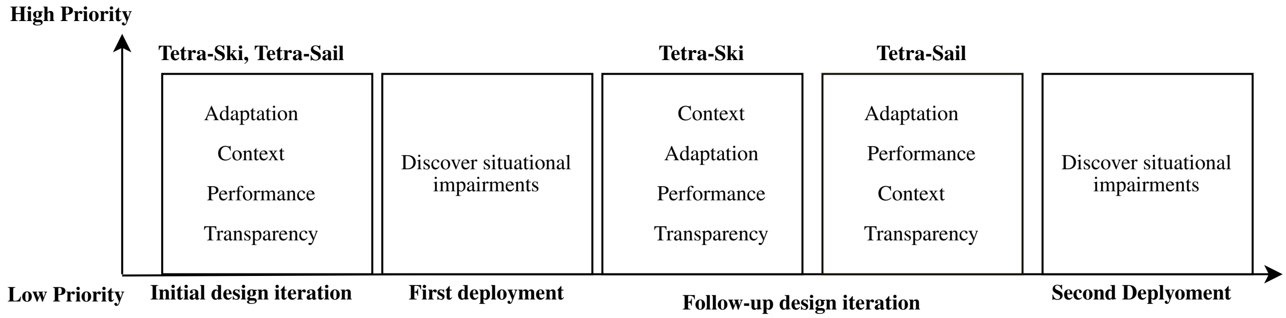

Figure 2: Our process applying and prioritizing ABD principles for Tetra-Ski and Tetra-Sail.

Adaptability and engagement

The principle of *adaptation* emphasizes designing to match the abilities of the user. In terms of challenging activities, the adaptation principle dictates that the system, not the user, should change to increase usability. Although this goal is meritorious, there is a risk in leading the user to perceive the presented task as too easy - which might diminish engagement. Accordingly, there is a distinction between the ease of use of the interface and the ease of completing the task. For the purposes of the control systems described in this manuscript, we attempted to maintain ease of use for the interface (i.e. sip-and-puff commands), while maintaining the challenge in the activity at hand (e.g., ski, sail). While these may sound like easily separable goals, in practice this is a notable design challenge. For example, at what point do the interface features cross the line from adaptation to unwanted support? This question has value for a range of design approaches, and is especially pertinent for designing adaptive recreation technology. Individuals with disabilities are consistently hampered by social barriers, including inadequately designed technology, that directly limit independence and autonomy. Designing technology to effectively adapt to a person’s ability without imposing barriers - under the guise of support - is critical for these groups to have optimal engagement opportunities.

Context is also a critical concept for adaptive design. For example, the Tetra-Sport experiences are influenced by real-world variables (e.g weather, gravity) that are either difficult to control for or uncontrollable. In our deployments, there were numerous examples in which a control partner worked with the participant to adapt to contextual challenges in order to manage the difficulty of the experience to prevent it from becoming too hard *or* too easy. These variables illustrate the need for adaptive difficulty. Adaptive difficulty can be described as the process of monitoring user performance, environmental conditions, and factors, and adjusting the system to match the user’s abilities, performance, and surrounding context. This is illustrated when contextual factors, like weather, influence the difficulty of the activity, but is also observed with controllable factors related to the technology design. We believe it is the responsibility of the technological system - in this case, the control partner - to adapt for the benefit of the main user. This approach has benefited our participants, but the technology is not yet ready to sense contextual factors and enact the necessary automatic adjustments to address in-the-moment contextual demands. We rely on the intuition and experience of our control partners, but our goal had been to integrate automated systems modeled after each participant’s abilities. For example, the control partner will often have to determine the degree of challenge for the user when deciding whether to intervene. Despite our goals for automation, participants provided positive feedback about this dynamic Shared-Control approach, causing us to reconsider our goals.

Adaptation and engagement are also highly related to the nutrients that motivate participation in activities. Outdoor sports offer an ideal platform for fulfilling these needs, such as making self-directed choices, achieving mastery at tasks, and facilitating positive human interactions. These opportunities are in line with basic psychological need fulfillment, a central concept to motivation theory [32]. These needs include: autonomy, competence, and relatedness. In practice, humans are motivated to engage in activities when they perceive the ability to choose, be effective at a task or demonstrate mastery despite the challenge, and do so in positive connection with others. Conversely, humans tend to disengage when they have limited choice, perceive tasks to be unattainable, or lack positive engagement with others. These psychological concepts demonstrate a valuable challenge to address in ABD. Specifically, technology will facilitate optimal engagement when it can pivot to address these needs. These concepts are especially pertinent to the design of adaptive recreation technology. Individuals with disabilities often experience wide-ranging social and physical barriers that hinder autonomy, competence, and relatedness - especially with regard to technology. Designs that address these needs will enhance engagement.

Bridging the gap to ABD with Shared-Control

Shared-Control was initially implemented as a design solution for the Tetra-Sport activities out of necessity. The goal was to provide a recreational service for users with tetraplegia while maintaining user safety. Shared-Control afforded the flexibility to safely deploy the prototype systems in a real-world context with participants from the target population.

The real-world deployments demonstrated a range of successes and challenges. Importantly, it helped us better understand the physical limitations of our participants when undergoing long, active sport activities and offered us insights into users behavior and reactions to potential risk in our experience.

Based on the experience of applying Shared-Control in these early prototypes and the success of the resulting prototypes, we found Shared-Control to be a valuable tool for prototyping adaptive technology experiences. This has similarities to a Wizard-of-Oz prototyping approach or other human computation approaches that are already common in the accessibility literature [24]. For the purposes of the designing the Tetra-Sport experiences, we determined that Shared-Control was the primary mechanism by which principles of ABD (e.g., context, performance, adaptation, transparency) were supported.

We developed the Shared-Control system components over multiple iterations of deploying the systems. Through this process, feedback data from users and control partners were collected and applied to redesign. Delineated below are some insights that we developed in this process that can springboard others who seek to design Shared-Control systems:

Communication - Building on ABD’s principle of transparency, effective communication between the user and the control partner is essential. However, this goal can be somewhat of a challenge in this context. For example, when skiing, the control partner is able to shout short phrases to the user, but the user has limited options for communicating back to the control partner. The control partner can see and react to the user’s gross movements on the joystick, but not with the sip-and-puff. Tetra-Sail facilitates easier communication. We also added a bluetooth speaker to give feedback on the sip-and-puff commands to facilitate effective communication between the main user and control partner.

Relatedness - Positive connection and trust between the main user and control partner was essential to a successful Shared-Control experience. This is in line with the basic psychological need of relatedness in SDT [7]. For example, the main user and the control partner benefited by mutually working towards a shared goal of a playful and safe experience. A remote control allowed the control partner to make minor adjustments to the system without fully overriding the main user’s control. This also builds on the idea of interdependence [4]. Participants reported appreciation of this collaborative engagement.

Technology fidelity - In addition to a positive relationship with the control partner, Shared-Control was most effective when the users trusted the system. Throughout the iterative development, when participants expressed higher levels of trust, we observed fewer interventions by the control partner and greater opportunity for the main user to explore the technology. However, if the users did not trust the system, the control partner was observed to preemptively intervene.

Autonomy - Agency in the midst of Shared-Control is a challenge, but critical for user needs. Participants expressed satisfaction when their experiences were characterized by high levels of self-direction. This highlights the importance to defining boundaries between control, Shared-Control, and autonomy in future designs.

Control Options - Success of Shared-Control was also related to the control options available to the control partner and the main user. For example, the control partner was able to make small adjustments periodically without fully taking that control away from the user. While we were concerned that intervention of any kind might affect autonomy, participants found these capabilities reassuring and largely appreciated control partner interventions when they were aware of them.

Competence - To enhance the perception that the tasks were achievable, we leveraged previous skills for the control-partner and the participants using our systems. This is highlighted with using technology that was familiar to the users. For instance, the control partner used the same technology for other adaptive skiing activities. The main users had opportunities to use similar joystick/sip-and-puff systems many of them use to control their wheelchairs. These users also had the opportunity to use a simulation that would allow them to become comfortable with the control scheme and input device ahead of the real-world experience. This design decision built upon on the users’ existing knowledge and set of skills to enhance a sense of competence with the activities.

Extending ABD goals for sport activities

ABD is primarily focused on maximizing accessibility and usability for an assistive technology. Accessible sport activities share the same goals, but with an eye towards providing the "right" amount of challenge for the users to maintain flow and providing appropriate levels of autonomy and competence. We find ABD in its current incarnation to be a necessary, but not sufficient, framework for capturing how we have designed and implemented Tetra-Ski and Tetra-Sail. In these cases, there were important considerations for *safety* and *enjoyment* that we had to balance against other ABD goals. We think it is essential in these situations for designers to balance and weight the priority of different ABD principles in designing their adaptive sport systems. We used Flow and SDT as a way of operationalizing enjoyment to balance adaptation and performance implementations for our experiences. Different system contexts may have their own additional factors to consider, but for us *safety* and *enjoyment* were our primary additional considerations, and we believe they are a good start for others looking towards ABD for guidance when designing accessible sport activities.

CONCLUSION

Designing outdoor activities for individuals with acquired tetraplegia requires careful design and consideration to provide a usable, enjoyable experience. ABD offered a useful lens to help shape our systems to best match our users’ abilities. Our development process revealed the need to have a human engaging in the experience with our participants to maintain safety and reduce anxiety. Shared-Control is our solution to this design challenge. Results from deploying these two systems indicate that Shared-Control allowed for safe and enjoyable experience with a gentle learning curve. Building on this we think the need to consider expanding the ABD principles for outdoor activities to include design goals such Autonomy, Competence and Shared-Control system is essential for successful deployment especially at the early stages of the development process.

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