The Augmented Climbing Wall: High-Exertion Proximity Interaction on a Wall-Sized Interactive Surface

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ABSTRACT
We present the design and evaluation of the Augmented Climbing Wall (ACW). The system combines computer vision and interactive projected graphics for motivating and instructing indoor wall climbing. We have installed the system in a commercial climbing center, where it has been successfully used by hundreds of climbers, including both children and adults. Our primary contribution is a novel movement-based game system that can inform the design of future games and augmented sports. We evaluate ACW based on three user studies (N=50, N=10, N=10) and further observations and interviews. We highlight three central themes of how digital augmentation can contribute to a sport: increasing diversity of movement and challenges, enabling user-created content in an otherwise risky environment, and enabling procedurally generated content. We further discuss how ACW represents an underexplored class of interactive systems, i.e., proximity interaction on wall-sized interactive surfaces, which presents novel human-computer interaction challenges.

Author Keywords
Human-computer interaction; sports; climbing; movement-based games; exertion interfaces; augmented reality

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
Utilizing technology to increase excitement and motivation in physical exercise and sport has been increasingly researched in both HCI and sport science [2, 30, 32, 33, 43]. Computer-generated feedback has also been used to enhance movement skill acquisition [23, 26, 37]. However, almost all the studies have been conducted in laboratory setting or as one-off experiments where researchers actively participate in the experiment. Studies in the real world can reveal new aspects of interactive technologies, as participants use the technology on their own terms and without supervision [35].

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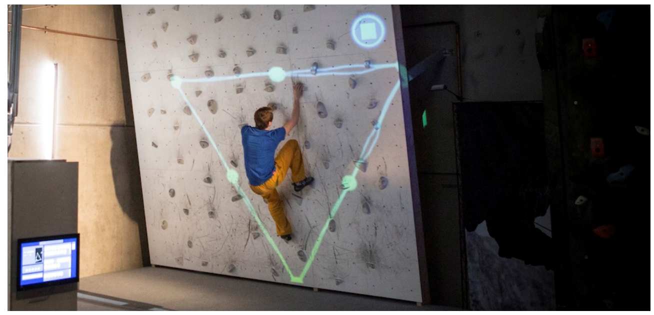

Figure 1. Our augmented climbing wall in a climbing gym. The climber is playing the Spark game, where the goal is climb from start to end (indicated by stop button) while avoiding the moving electricity lines. The bottom left corner shows the touchscreen used, e.g., to browse game levels. The touchscreen is attached to a cabinet hosting the computer and a Kinect V2 sensor. The projector is mounted on the ceiling.

This paper contributes to the limited knowledge of designing technology and movement-based games[1] outside the laboratory, in real-world sport environments. We have set out to study how climbers interact with technology in a climbing center. This is motivated by the relatively few previous studies on indoor climbing, despite it being a rapidly growing sport [7, 38] and being considered for inclusion in the Olympics [6]. We investigate the following questions that impact the design of interactive systems for sports:

- What are the opportunities and challenges of augmenting a sport with interactive technology?
- How does interactive technology change a sport? More specifically, in what ways can technology affect climbing or watching someone else climb?

Figure 1 shows our Augmented Climbing Wall system installed in a commercial climbing center. ACW combines projected graphics and depth camera body tracking to create interactive games and other training applications. ACW also includes a separate touch screen for more detailed and multiuser interaction, although we do also provide projected buttons on the wall for basic actions such as restarting a game level.

ACW is designed as a research instrument for probing the questions above, and also to solve the problem of providing several interesting climbing challenges and activities in a

[1] By movement-based games we denote games that require active full-body participation [32]

small space. Climbers constantly yearn for new routes to climb (problems to solve), and as shown in Figure 2, fitting multiple routes in a small space easily introduces visual clutter and creates undesired challenges in finding correct holds. Projected graphics allow us to clearly highlight different routes and game levels that reuse the same set of holds. Climbers can quickly browse through the levels, avoiding the sometimes tedious search for routes suitable for one's skills.

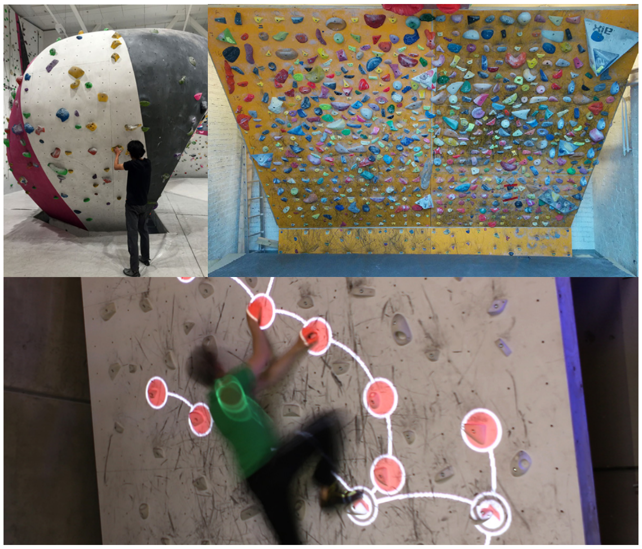

Figure 2. Top left: A climbing wall with color-coded routes. Top right: Adding several routes to a small wall may produce a visually cluttered result. Bottom: projected graphics highlight the holds, reducing clutter.

In this paper, we describe the ACW system and three interactive applications (2 games, 1 game level editor). We also present the results from installing ACW for daily use in a climbing gym for four months. Data was gathered in three user studies and by logging game events. We first review related work, then present the system and the design of the applications, and describe the three user studies (N=50, N=10, N=10). Based on the studies and our further observations, we highlight three central opportunities and challenges of augmenting a sport with interactive projected graphics.

RELATED WORK

There has been a substantial amount of research on climbing, mostly concentrating on physiological and biomechanical aspects [9, 29, 41]. The mental side of climbing has also been studied [11], especially the influence of danger and physical risk [25]. There has been less research on using technology, with an exception provided by Climbax [22], which provides climbing statistics by utilizing sensors embedded in a wristband. Similar wrist worn inertial units can also be used for recognizing climbed routes in a climbing gym [21].

In the intersection of climbing and HCI, interactive climbing walls have been developed before our work, but the prior systems have concentrated on attaching sensors and lights to climbing holds [15, 24], or have not utilized full body tracking [40, 45, 46]. Compared to this, our projector and camera setup has many benefits 1) full-body motion tracking for movement analysis and interaction, 2) real-time feedback and interaction with projected graphics, 3) projection on the entire wall instead of just the holds, 4) a configurable system for any climbing wall, and 5) recording the performance for instant replay or later analysis.

Climbing routes (a.k.a. problems) are often "solved" socially with others. The mobile augmented reality application BouldAR by Daibler et al. [8] emphasized the sharing, collaborative training and other social features by providing a way to create, share and define goals and challenges together with friends. Daibler et al. conducted a promising initial study comparing paper and smartphone based route creation, but they underline that collaborative training needs to be explored more in detail. Our work enables collaborative training where climbers can jointly create, edit, grade, comment and share climbing routes by using a touchscreen.

Considering technology and sports on a more general level, there exists a growing body of work on enhancing motor learning and performance using computer-generated augmented feedback (AFB), such as sound effects or visuals that highlight salient aspects of one's performance. When designed properly, AFB can both motivate and guide motor learning [26, 37, 42]. Computer generated feedback can be faster and more accurate than training with a video camera or receiving feedback from an instructor, which allows one to perform more repetitions and evaluations of a skill in a shorter time. Concurrent (i.e., real-time) visual feedback can especially benefit the initial learning of complex skills [37]. However, it should be kept in mind that the learner may develop a dependency on AFB, as explained by the guidance hypothesis [26]. Outside a strict motor skill acquisition focus, we are especially inspired by work such as Jensen et al. [17] and Mueller and Muirhead [31] that derives design knowledge through the study of athletes' experiences of incorporating experimental interactive systems to their practice.

Our key technological components are computer vision and interactive projections, which have a long history in HCI and movement-based games, with examples like the Ping Pong Plus augmented table tennis [16], artificial reality martial arts [12], Kinect trampoline games [14], as well as RoomAlive [18], where multiple computers, cameras and projectors can be calibrated together to transform an ordinary room into a game space.

RELATION TO THE PRELIMINARY ACW STUDY

This paper continues an earlier preliminary study where we developed and evaluated six interactions with eight climbers [19]. For completeness, we briefly review the interactions here:

- **Projected routes**: Projected routes with illuminated circular holds and connecting lines. See Figure 3 left.
- **Route building**: A new route can be defined by climbing. All holds that the climber's hands or feet touch are included in a route.
- **Delayed video feedback**: Falling from the wall triggers a video replay.
- **Hand marks**: A person waiting for their turn uses left and right mouse buttons to define targets for the climber's left and right hands.
- **Route automator**: Endlessly progressing route for endurance training. The system reveals a new random handhold when the previous hold is reached. See Figure 3 middle.
- **Animated Chainsaw**: Climbers avoid animated chainsaws. See Figure 3 right.

Figure 3. Interactions from our earlier, preliminary ACW study [19]. Left: projected routes. Middle: route automator. Right: animated chainsaw.

We build on the preliminary study in three ways: 1) The preliminary study interactions were tested in a light-weight Wizard-of-Oz manner, but our system is technologically complete with computer vision, projector-sensor-calibration, and an additional touchscreen interface for switching and configuring the interactions. 2) We have chosen the three interactions of Figure 3 and developed them further to a level where they work autonomously in a commercial climbing gym. 3) We evaluate the interactions based on three user studies, providing novel data for understanding augmented sports.

INTERACTION DESIGN

This section describes the design of our three applications: the Spark game, Route creation, and the Whack-a-bat game. The applications are illustrated in Figure 1, figures 4-7, as well as the supplemental video.

The high-level interface for selecting and configuring the applications is implemented on the touchscreen shown in Figure 1. In general, our approach is to minimize interface elements such as buttons projected on the climbing wall itself. In principle, everything could be implemented with a projected interface, but using the separate touchscreen yields far more precision, e.g., when editing a route or browsing a large number of user-created routes.

The Spark Game

Evading the chainsaw was the interaction that elicited most excitement in the preliminary work, although some climbers did remark that it is quite far removed from regular climbing. The main change we have made is updating the game theme to avoiding moving electricity lines instead of chainsaws. This allows us to create obstacles of arbitrary shape, and makes visuals less ambiguous; with the chainsaw users were not sure whether they could touch the handle. The resulting Spark game is shown in Figure 1 and Figure 4. The game starts when the user taps the play button, after which the goal is to get to the stop button without touching or overlapping the electric lines. The lines may be static or moving, and some levels also have intermediate waypoints that open up new passages or otherwise change the level.

Although the spark game introduces new aspects to climbing, our goal was to preserve the following familiar and motivating aspects of climbing:

- Each game level has a clear start and end.
- The moves can be planned beforehand and executed while climbing, thus creating both cognitive and motor challenges.
- Each level is predesigned (as opposed to, e.g., randomly created) so that it can be practiced and one can learn from the performances of others.

Route creation and climbing

Our second application combines and further develops the projected routes and route building interactions of the preliminary study. Our touchscreen interface is shown in Figure 6. The screen shows the Kinect RGB view of the climbing wall. Touches are mapped to projected graphics coordinates by using the Kinect 3D coordinate information of each pixel and projector-sensor calibration data. Touching a hold adds or removes a hold mark and an arc between holds. The created routes can be browsed by grade, ratings, times climbed or tried and time of creation. Climbers can also vote for a route grade, input a 1-5 star rating, and add comments.

We first attempted to allow climbers to design routes by climbing, but could not find a 100% reliable way of detecting which holds were used and should be included in a route. In some routes, the climber's whole body may hug the wall closely and cause erroneous selection of holds. It appears that there should be at least some way to edit and refine the route information, which is why we designed and implemented the touchscreen editor. Perfecting the automatic route detection is left as future work. In the end, it turns out to be a fun social activity to edit a route together with a friend, one person using the touchscreen and the other trying out the moves on the wall. This is in line with the positive comments about the sociality of the hand marks interaction of the preliminary study.

The Whack-a-Bat game

Our third application is the Whack-a-bat game (Figure 7), where one attempts to touch a bat sitting on the holds before a timer runs out. When a bat is touched, it flies to a random location on the wall and restarts its timer. The new locations are randomized so that they never overlap the climber's body. As the game progresses, more bats appear, escalating the challenge.

Whack-a-bat extends the idea of the endless route automator of the preliminary study. We chose Whack-a-bat as our third application due to user and climbing gym staff requests about an endless endurance training application. We also wanted to add a simple way of competing with others and monitoring one's own progress in a longer term.

In the first iteration of Whack-a-Bat, the bat simply appeared at each new location, and the users often had difficulty locating it. In the present version, the bat's flight between the holds is animated with ease-in and leaves clear trails. This is inspired by Chang and Ungar [4] who propose using cartoon animation techniques for making it easier for users to track objects and understand what is changing. However, the animation alone is not enough to make it easy to track multiple bats, as the climber is close to the wall and cannot view all of it at a glance. To fix this, the bats also broadcast their locations using visual beacons, i.e., expanding circles that allow one to infer the directions even when looking elsewhere. Previously, Khan et al. [20] have suggested dimming the brightness of other elements to point out the location of a specific object on a large screen, but this is not necessarily compatible with a game's visual design, and only works if one can see the whole screen.

CLIMBING WALL SETUP AND TECHNOLOGY

The ACW hardware setup comprises a climbing wall, Windows PC, Kinect V2 depth and color sensor, a projector, and the additional touchscreen. Presently, we have two setups, one at our university, and one at a climbing center. The wall dimensions are approximately 4 x 2.7 and 4.5 x 3.6 meters. While this is not enough for rope climbing walls, such wall height is common in indoor bouldering, which is a rapidly growing segment of climbing [7, 38]. Bouldering denotes climbing without a belay rope on low rocks or walls, with mattresses for safe falling. We use a 50cm thick mattress covered with carpeted polyethylene foam mat, which can be seen in Figure 1. We have further ensured safety by using a slightly overhanging wall. This way, climbers are less likely to scrape themselves against the holds when falling.

Wall size limitations

The climbing wall size is limited by the Kinect's field of view (FoV) and depth measurement noise that increases with distance. A large wall requires placing the sensor far, which makes it difficult to discern details such as fingers from noise. Our sensor is placed at approximately 3.5 meters from the wall. A system designed for adults might work with a sensor further away, but the small hands of

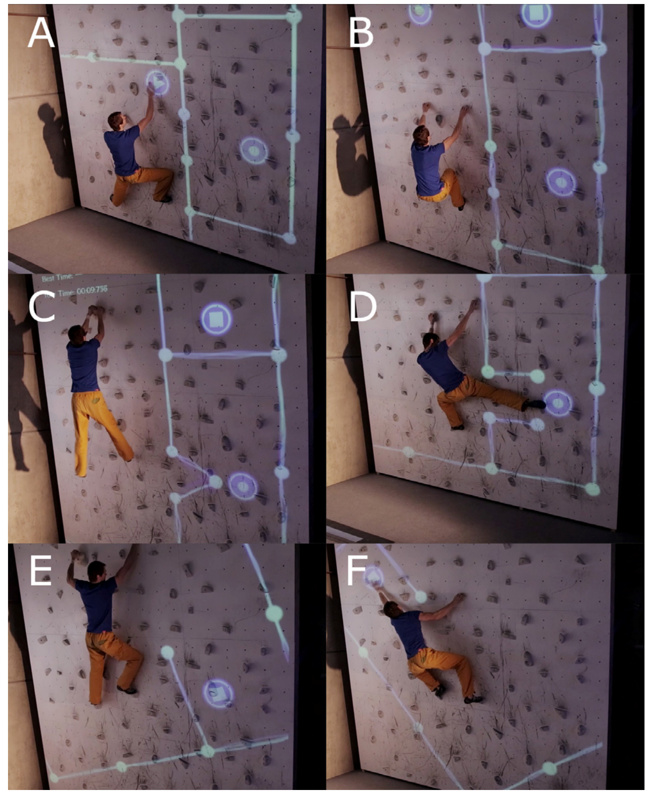

Figure 4. Progress of one game level A) starting the level using the play button, B) Timing a jump to avoid a blinking horizontal electricity line, C) Touching a waypoint opens a door, D) The second waypoint is reached with a challenging move, E) The whole level starts rotating and the climber needs to catch the moving stop button, F) Hitting the stop button ends the level.

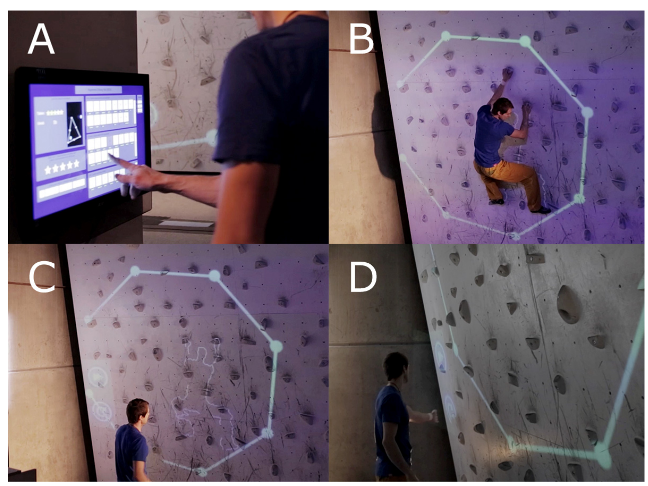

Figure 5. A) A touchscreen can be used to select different game levels and grade the levels (1-5 stars overall rating and a difficulty grade using the French climbing scale). B) The game stops with blue flashes and sound effects when intersecting a line. C) A burn mark silhouette indicates body pose at the time of intersecting the electricity. D) The game level can be restarted using a button on the wall, which is faster than using the separate touchscreen.

children become a problem. Figure 8 shows examples of the depth sensing resolution and noise at various distances. At first, we also tried to implement the system using the older Kinect 1 sensor, which turned out too noisy. In a Kinect 1 depth image at 3.5 meters, one cannot even discern climbing holds from the noise. We have also investigated other depth sensing technologies, but the Kinect V2 appears to provide an unmatched combination of low price, high angular resolution (512x424 pixels with FoV of 70.6x60 degrees, i.e., roughly 7x7 pixels per degree), enough range, and high enough frame rate (30fps) for tracking dynamic movements.

Computer vision

We use custom computer vision software, as the Kinect V2 default skeletal tracking and user detection was found unreliable when not facing the camera and hanging on the wall. This is to be expected as the tracker is heavily based on machine learning training data captured from people's living rooms [36], and the data is unlikely to include the body poses typical to climbing.

When the system is started, we obtain a one second average of the depth map of the static background. At subsequent frames, we perform basic background subtraction, i.e., we segment the pixels to foreground or background by comparing the depth values to the background average. This is straightforward except that one must carefully filter the pixels near foreground object edges, where the depth readings randomly vary between the foreground and background distances. The foreground pixels within 2-8 cm of the wall are labeled as touch points and used for detecting the pressing of projected buttons (e.g., the play and stop buttons of the Spark game). The touch depth range is constrained by both depth noise and occlusions. The upper limit of the range must be quite high to accurately detect touches when the actual point of contact with the surface is occluded by the user's hand or foot.

All foreground points are used for detecting intersections with the electricity lines of the Spark game. Here, the 2D lines are actually considered to signify 3D planes that protrude from the wall, perpendicular to it.

Calibration

Calibrating the system consists of three phases: 1) aligning the projector and sensor so that the wall fits inside their frustums, 2) software keystoning, i.e., the user drags the four corners of a projection rectangle to define the active interaction area on the wall, 3) the software projects a dot pattern and detects the dots by comparing the Kinect's RGB view to a reference image stored before the procedure, and 4) the dots are used to compute the transformation matrices between the game graphics coordinates and the 3D coordinates provided by the sensor. At the climbing center, we ran steps 1 and 2 once, and the software runs steps 3 and 4 every morning when the computer is turned on. We have found this adequate, provided that the Kinect is mounted firmly.

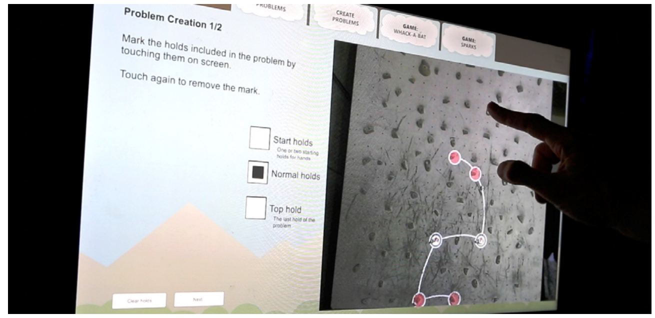

Figure 6. The touchscreen route creation interface.

Figure 7. The Whack-a-bat game. The player scores by touching a bat, after which it flies to another position. The bats emit circular enlarging beacons to help in spatial perception. More bats appear as the game progresses.

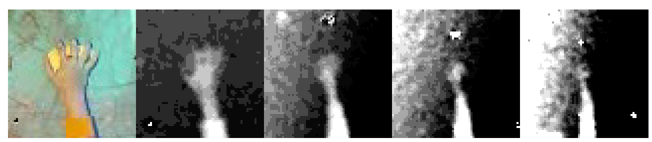

Figure 8. An adult climber's hand on a climbing hold, and corresponding Kinect V2 depth images at distances of 2, 3, 4, and 5 meters.

The game graphics are positioned within a 2D rectangle that is mapped to the projection rectangle. The applications all use 2D graphics which are faster to design and work without low-latency player viewpoint tracking.

USER STUDIES

Our ACW system was first developed at our laboratory and then installed at the Boulderkeskus Isatis climbing center in Helsinki, Finland, May 2015. At the time of submitting this paper, the system had been running for 4 months except for a 4 week break when waiting for a replacement projector. During the time, we conducted one primary user study (N=50) and two supplemental studies (N=10). The primary study 1 investigates the Spark game using questionnaire data, study 2 continues with questionnaire data from all three applications, and study 3 compares two Whack-a-bat interface versions. We also logged game usage data, which we summarize at the end of this section.

Study 1: Spark game questionnaire

In the beginning of our testing period, we only had the Spark game functional, and the other interactions were

Q1: What did you like the least?		Q2: What did you like the most?		Q3: Differences to regular climbing.		Q4: Differences to spectating climbing.		Q5: Suitablility.		Q6: Benefits for climbing practice.	
Category	**N**	**Category**	**N**	**Category**	**N**	**Category**	**N**	**Category**	**N**	**Category**	**N**
Tracking Failure	15	Different / Novelty	18	Climbing Style / Positions	9	Social / Participatory	16	Everyone	23	Endurance	11
User Interface / on Wall	13	Other	16	Tempo	8	Fun	12	Children	14	Other	10
Climbing Routes / Perceiving	12	Fun	12	Climbing Routes / Planning	8	Excitement	9	Other	7	Speed	8
Physical Environment	5	Variety (of routes / training)	12	Concentration / Focus	7	Other	8	Beginners	7	Movement Variety	8
Cheating	5	Motivates Movement Variety	6	Other	7	Nothing	5	Youth	4	None	6
Soundscape	3	Moving Routes	5	Competitiveness	4	Soundscape	3	Groups	3	Concentration / Focus	4
Climbing Routes / Planning	2	Motivates Endurance Training	4	Endurance	3	UI	2			Warm-up	3
Tempo	2	Idea	4	Fun	3					Training small holds	3
Visual Design	2	Fear of Heights	3	Fear of Heights	2					Dynamic moves	3
Difficulty	2	Competitiveness	2	Social	1					Technique	1
Other	2	Excitement	2	Excitement	1						

Table 1. Categories of the questionnaire responses, in order of frequency. Each response can belong to more than one category.

installed in late August. We gathered user feedback from the Spark game using a questionnaire. Printed questionnaires were available at the bouldering gym, and courtesy of the gym management we were able to raffle free climbing passes among respondents who answered all questions. A total of 50 climbers submitted the questionnaire (29 male, 19 female, 2 other. Age median 27, sd 6.9. Climbing experience median 2 years, sd 2.8. Climbing activity median 2.5 times per week, sd 1.2. Maximum climbed grade median 6c, French grade system).

Our questionnaire included eight open-ended questions: Q1) What did you like the least? Q2) What did you like the most? Q3) How does climbing in the game differ from regular climbing? Q4) How does watching someone play differ from watching regular climbing? Q5) Who is this most suitable for? Q6) Would this help your climbing practice? How? Q7) The game had both static and moving levels. Which were better? Why? Q8) Other comments?

Here, we focus on Q1-Q6. Answers to Q7 were inconclusive, and Q8 mainly prompted generic compliments that highlight the overall positive response. To summarize the results of Q1-Q6, two independent coders categorized the responses with a rate of agreement of over 92% for each question. Answers may belong to multiple categories, so typical intercoder reliability statistics such as Cohen's kappa are not usable. The categories and their frequencies are shown in Table 1. The following elaborates on the most relevant findings.

The climber's experience: diversity, fun, forgetting one's fear of heights

Responses to Q2 highlight the versatility, fun, and excitement that the game adds: *"Diverse training"*, *"Fun, new things to do for a climber"*, *"Versatile and different. Moving levels are more fun."*, *"I noticed I was climbing more in a short time as I had to try again and again :)"*, *"Many routes in a small space. Creates diversity in climbing."*, *"Easy to change the wall and level of difficulty."*, *"Forces one to quickly search for alternative routes since the boundaries are moving."*, *"Fun endurance practice that does not feel like practice. Makes one sweat, panic, and laugh :)"*

Q3 responses further elaborate on the novel challenges of the Spark game regarding endurance, variety of movements, and spatial awareness: *"Movement is different, more sideways movement."*, *"More different moves",*, *"Must do more work on the wall (harder to plan the route <before climbing>)"*, *"One chooses the holds oneself and also moves downwards"*, *"Faster pace makes it more addictive"*, *"Must look at other things besides just the holds"*, *"Forces one in strange poses such as head downwards. Forces changes of tempo."*, *"One must observe sideways and downwards directions as well, can't rest so much"*, *"Spending a longer time on the wall"*. Movement variety was also among the most often cited benefits in Q6, in addition to endurance and speed. The appreciation of endurance training is a significant result, as low bouldering walls typically provide more strength than endurance challenges. The "speed" category of Q6 responses also indicate that climbers appreciate being forced to train quick decision making and reactions.

We find it particularly intriguing that three respondents claimed the game made them forget their fear of heights, *"Really great grip practice! I forgot to fear heights and falling"*, *"Excitement provided by the game at one meter above the ground"*. We have also observed similar effects in our previous work on trampoline games [14].

Investigating the psychological mechanisms behind this are an interesting topic for future research.

Another specific point mentioned was practicing dynos, i.e., dynamic leaps, *"Dyno practice. Force me to do them in a fun way. Practice timing too."* Here, ACW provides an example of how digital augmentation can actually make training safer and less frightening. Dynos are fun and thrilling, but can also be too scary due to the risk of ripping one's skin painfully when grasping a hold mid-leap. The Spark game has dyno training levels where one only slams the stop button and then falls down. This avoids hand trauma but still allows one to practice the coordinated recruitment of both arms and legs that's needed for efficient high jumps on a wall. Jumping on a wall is substantially different from jumping on the ground, and requires considerable practice.

Interestingly, although digital augmentation might distance the experience from climbing's outdoor roots, one respondent claimed the opposite, *"It's closer to outdoors, because there's no marked route."* Spotting the holds of outdoor routes can be surprisingly hard if one has only practiced indoors with brightly colored holds.

The spectator experience: new forms of interaction with the climber

Answers to Q4 highlight how the new perceptual challenges of observing all directions and dynamically changing levels also change the spectator's role, *"More exciting, one could participate as a spectator by giving instructions related to the moving lines.", "More interesting and nice to give guidance and warn the climber about the electricity.", "One more often shouts 'HELP!','LOOK OUT!', 'AAAAA' compared to just shouting beta".* Beta is climbing slang for instructions. In general, spectating the game was also found more fun and exciting. Sound and visual effects also received positive responses.

Technological and perceptual issues

Q1 responses reveal that during our test period, ACW was still a prototype and not a finished product. Especially tracking robustness and/or communicating the limits of the technology were found to require more work. Users criticized the game for *"It was hard to perceive one's body on the wall -> easily hit the electricity", "Electricity borders are imprecise, difficult to estimate whether one's head or limb will hit the electricity",* and *"Detecting hits based on shadows instead of real body outlines"*. In reality the system is indifferent to the visible shadows of the user, and the comment simply indicates that there was some unpredictable behavior.

There appears to be two main failure cases: 1) tracking glitches due to occlusion and fuzzy object outlines such as hair, which cause random depth readings, and 2) the matching of a 2D shape on the wall surface and one's 3D body being up to interpretation. The first could be fixed by using multiple sensors and developing a custom model-based skeletal tracker to help in ignoring foreground point cloud outliers. The second is a design issue. We first considered detecting the electricity collisions only where one's body touches the wall. This was later discarded in favor of the present game where the electricity lines actually represent 3D planes protruding from the wall. Our rationale was that avoiding the 3D planes presents more interesting spatial puzzles. We believe that this approach is still valid as people clearly learn to play the game after getting "burned" a few times and observing the detected body outline rendered on the wall (Figure 5C). The body outline could also be rendered during play to make it explicit what the game detects, which we have so far avoided to minimize visual clutter and hide tracking and rendering latency.

Target audience: everyone, especially children.

As shown in Table 1, the most common answer to Q5 is that ACW is suitable for everyone (22 mentions). The next most common answers were children, beginners and "other", which comprises characterizations such as *"Everyone, especially people who like games", "Rich people's homes?", "Active climbers."* It should be noted that we deliberately equipped the wall with rather small holds that are more geared at intermediate and advanced than beginner climbers. The inclination of the wall (together with the smaller holds) also makes the wall really hard for beginners. On the other hand, the holds are easier for the small hands of children. During our visits to the climbing gym, we have observed children using ACW for several hours straight, which reflects the fact that adult routes are often too difficult for children and the gym only had little space for dedicated children's routes. It appears that ACW provides a space-effective way of expanding a gym's target audience to children.

A few Q3 responses highlighted negative aspects of how the Spark game changes climbing. *"In normal climbing, the routes are defined and one works on them if one fails. The game does not force one to work on the route and develop one's technique."* In light of this, the game might be more suitable for endurance and strength training or as a warm-up exercise rather than developing perfect climbing technique. Three answers to Q6 also praised the game for providing great warm-up. We conclude that designers should be cautious about how digital augmentation can both expand and limit a sport's target audience.

Study 2: Deploying Whack-a-bat and route creation

We installed the route creation and Whack-a-bat applications 4 weeks before the end of the study. We also made available an updated the Spark game questionnaire with a field that indicates the application(s) that one has tried. According to the 10 filled questionnaires we have received so far, the applications work as intended. Two respondents mention that Whack-a-bat is the best application, and three remark that it is a great form of warm-up. The data is generally in line with the Spark game

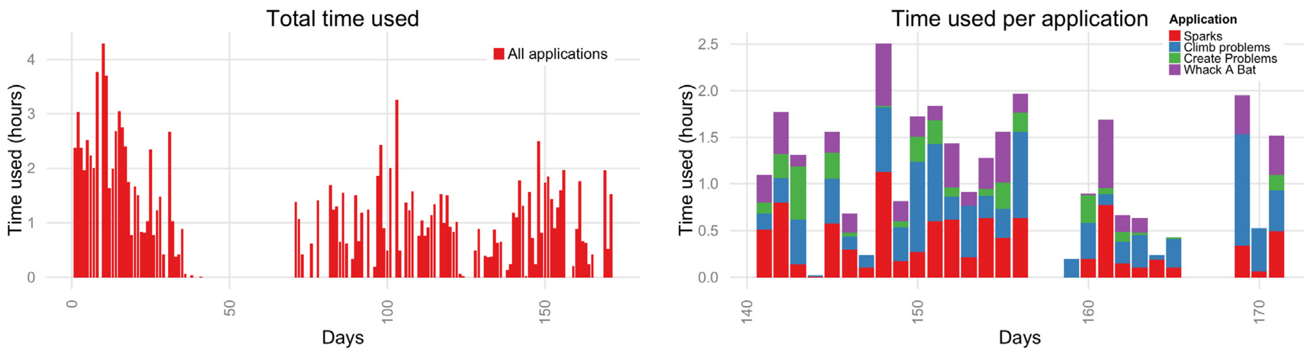

Figure 9. Left: Usage data from 171 days, May-September. Right: Breakdown of the last 30 days when route creation/climbing and Whack-a-bat were installed in addition to the Spark game. In addition to the maintenance break around day 50, there are several days of low or no usage due to the climbing gym being closed or the staff forgetting to turn the system on.

answers. According to our observations from visiting the gym, children in particular seem to like creating new routes, both for themselves and their parents.

Study 3: Improving spatial perception in Whack-a-Bat

Whack-a-bat attempts to improve the player's spatial perception using the circular beacons of Figure 7. Since such beacons are not commonly used and could also introduce undesired visual complexity, we conducted a within-subjects experiment to validate their effectiveness. 10 users were recruited from university students and staff. Each user played the game with and without the beacons in counterbalanced order. The bat transition animations were turned off for both game versions. After experiencing each condition, the users were asked to rate the difficulty of knowing at all times where the bat is on a 7-point Likert-style scale of 1=very easy, 4=not easy or difficult, 7=very difficult. The version with beacons was rated easy (mean=2.7, sd=1.4), and the version without beacons was rated difficult (mean=4.7,sd=1.4). A Wilcoxon signed rank test indicates that the difference is statistically significant ($p=0.0039$). After the test, the participants were also asked how the game versions differed, and how long it took them to realize what the beacons were for. 9 participants had noticed the beacons. All of them stated that they started using the beacon information after 1, 2 or 3 bats, which indicates that the beacons are fairly intuitive.

Game logs

An overview of game usage data is shown in Figure 9. The overall usage time of the system has remained relatively constant after the introduction of the system. The large gap around day 50 is due to projector malfunction and waiting for a replacement projector.

Towards the end, it appears that less new routes have been created and people have been spending more time climbing the already existing routes. We do not have enough data for reliable statistical analysis, but the shift in behavior makes sense as there are now enough routes for most climbers to find something interesting. A total of 53 routes have been created so far.

Further analysis of the data is hindered, because the number of daily climbers greatly varied due to it being summer and most people climbing outside if it was good weather. The duration for which ACW was turned on also varied from 0 to 11 hours each day. The climbing gym staff sometimes forgot to turn the system on at all, which is a result in itself – a system like ACW should not require even a single daily maintenance task for reliable data gathering.

DISCUSSION

To inform the design of future augmented sports, we now articulate the central opportunities and challenges that emerge from our data and experiences.

Opportunity 1: Increasing movement diversity and accessibility

The Spark game data highlights the positive effect of increased diversity of movements and challenges. In previous work, movement-based game players have found creative variation of movement as interesting and enjoyable [32]. Similarly, movement professionals often enjoy a playful exploration of the capabilities of the human body. As dancer and choreographer Steve Paxton puts it, *"I have a hunger to find, and to finish, and to explore, to do essentially what babies do when they begin to move. A hunger to find out more of what movement is or can be."* [1]. This is also in line with studies that have found curiosity as one of the central intrinsic game motivations [27, 28].

Climbing provides highly different movement challenges compared to movement-based games played on a floor, and the Spark game can be considered to further increase diversity in the following ways:

- The targets to reach can be anywhere, whereas in regular climbing the goal is to reach the top of the wall, from where one jumps down on a mattress or is lowered down on a rope. Climbing downwards requires different movements and skills and is often regarded as boring, but a game can make it meaningful and fun.

- In addition to targets to reach, there are also obstacles to avoid, which poses new challenges for spatial perception and movement planning.
- The obstacles and targets can move, which presents new timing challenges, e.g., jumping up or dropping down at the correct time.
- The game requires quick decision making and forces one out of one's comfort zone.

The increased diversity also appears to make climbing more accessible, allowing one to perform more attempts and succeed at least partially on a wider range of difficulty levels. For example, the level in Figure 4 is so hard due to the precise timing and coordination needed that even highly experienced climbers have had to try more than 10 times. Typically, routes of this difficulty are so physically demanding that one simply cannot perform multiple attempts in a short time. Routes above one's own climbing grade also often have so difficult holds that one cannot perform even a single move. As the Spark game is not so focused on grip strength, it is easier to make at least some progress on even the most difficult levels. Note that the importance of grip strength could be easily adjusted by using different holds. The reduced fear of falling and safer practicing of dynos also imply increased accessibility.

Opportunity 2: Enabling user-generated content in sport

The conceptual contribution of the route creation application is that it adds the ability for users to create and share content (routes, game levels) in a sport where one is not typically allowed to modify the environment because of safety reasons. Usually, only the climbing center staff or professional route setters adjust the holds, since an improperly secured hold can cause physical injury, and adding new holds without careful planning may block existing routes.

We believe our safe-to-edit digital content layer could be extended to other sports as well. This can be motivated by the game industry success stories of publishing a level editor together with a game, which can help build a long-lasting following and community around a game, with examples like Little Big Planet, Cities Skylines, and Trials Evolution [44, 47, 48].

Opportunity 3: Enabling procedural content in sport

Whack-a-bat can be considered as a simple example of procedural generation of the augmented digital content layer. Related to this, procedural game level synthesis is an active field of research [13]. In the context of climbing, some progress has been previously made in synthesizing textual route "recipes" such as "R slopey ledge, L match, R medium crimp sidepull…" [34]. In our experience, procedural content in sport is particularly suitable for motivating endurance training, where one can easily run out of handcrafted content.

We find both user-generated and procedural content especially important because they reduce the need for manually adapting content for the physical environment. Presently, we only have two flat walls of nearly equal size, but we have already experienced difficulties in playing the same game levels or climbing the same routes on both walls. Game feel depends on the hold sizes, shapes, and orientations. Further, scaling the visuals has a strong effect on the difficulty of maneuvering between Spark game electricity lines. Adapting content for different 3D wall shapes is even more challenging. Similar problems are likely to be encountered when augmenting other sports with varying physical environments, e.g., skateboarding or parkour.

Challenge 1: Understanding Proximity Interaction on Large Interactive Surfaces

The Spark game data indicates that people sometimes have difficulties of being aware of the extents of their body in space and in relation to the projected graphics. The iterative prototyping and testing of Whack-a-bat have further confirmed that ACW presents an uncommon combination of human-computer interaction challenges:

- Although people around see the whole screen, the person interacting on the wall (at an arm's length) only sees a portion of it at a glance. One's own body also often occludes a portion of the view.
- Due to gravity, the user must stay close to the surface at all times and cannot step back to view the whole.
- Staying on the wall requires heavy exertion and paying attention to holds, which limits the attentional capacity available for other tasks.

We believe that somewhat similar challenges may be encountered in other sports as well, e.g., when designing interactive visuals for a dance floor. More research is needed on interaction techniques that work in such settings. Vision is of course not the only sense that can be utilized, as suggested by Black and Loviscach's research on positional audio for large displays [3].

Challenge 2: Preventing Cheating

The Spark game leaderboards feature several implausible high scores (very low times between pressing the play and stop buttons), which are due to cheating. The most common cheating method we observed was to use two players, one for each button.

The lesson learned is that digital augmentation can introduce cheating even in a sport otherwise strong in self-regulation. Climbers usually avoid cheating despite the ample possibilities. In indoor climbing, the routes are typically color coded, a single wall has holds of multiple colors, and it is up to the climbers to stay honest and only use the correct holds. On the other hand the cheating is not surprising in light of previous gamification studies (e.g., [5, 10]). The Spark game leaderboards add extrinsic goals and motivation to climbing, and it has been found that an extrinsic goal orientation (a desire to engage in learning tasks because of extrinsic goals) is associated with cheating

[39]. It remains as future work to prevent cheating, e.g., by upgrading the computer vision to detect how many persons are on the wall, and focusing on supporting intrinsic instead of extrinsic motivation.

Challenge 3: Robustness and adaptivity to real-life conditions

In our experience, off-the-shelf electronics are vulnerable to the fine magnesium carbonate dust that floats in the air due to climbers applying the substance to their hands. The dust is not necessarily visible but still accumulates on everything, as illustrated in Figure 10. Our first projector drastically degraded in brightness during the first few weeks. In service, it was revealed that the dust had infiltrated the light source container. The lesson learned is that for prolonged use, one cannot avoid investing in hermetically sealed or otherwise dust-proof hardware. Magnesium carbonate is also used in other sports such as gymnastics.

Figure 10. Magnesium carbonate dust quickly accumulates on everything in a climbing center.

Another problem is presented by vibrations caused by people jumping off the walls. Such vibrations are also encountered in other sports such as weight lifting and gymnastics. We mounted our projector on the ceiling, and the resulting long projection distance makes vibrations highly visible – the graphics shake with an amplitude of several centimeters whenever a climber jumps off a nearby wall. Depending on sensor rigging, the vibrations could also interfere with computer vision.

Considering environments beyond our two present setups, we need to expand ACW from small and planar walls to larger and richer 3D shapes. As described earlier, it is a challenge to automatically adapt routes and game levels to different walls, which is however desirable if one aims at a low-cost system that can be installed anywhere without building a new wall. It also remains a technical challenge to accurately track a climber on a large wall with as simple camera setup as possible. The Kinect V2 has a limited range, and affordable long-range depth sensors have limited angular resolution. One solution could be to infer depth and 3D shapes from multiple high-resolution RGB cameras, but it remains unclear how fine precision one can achieve, e.g., for detecting when a climber touches a hold.

CONCLUSIONS AND FUTURE WORK

We have presented Augmented Climbing Wall, a novel sport training and movement-based game system with three prototype applications. The system has been received well, and the Spark game level in Figure 4 was even used as one of the competition problems in the Finnish bouldering cup final competition of 2015. According to our interviews with climbing gym staff members, ACW also makes birthday party and school groups climb for a longer time, and people making bookings have specifically asked whether ACW is available.

Our work highlights three opportunities in digital augmentation of a sport. First, interactive augmented visuals can increase the diversity of movements and challenges, e.g., timing of moves in an otherwise strength-centric sport. Second, a digital malleable content layer can empower users to become content creators with low risk compared to allowing users to actually modify the physical environment. Third, the digital content can also be procedurally generated, which is useful especially for endurance training sessions of non-predetermined duration. Other noteworthy findings include increased spectator-athlete interaction and users forgetting their fear of heights.

We have also highlighted three challenges that provide pointers for future work: 1) facilitating perception and interaction when close to a large display, 2) avoiding and preventing cheating when adding extrinsic motivators such as leaderboards, and 3) improving robustness and adaptivity of technology in real-life sport environments.

Considering generalizability, a climbing gym represents a class of sport environments characterized by 1) challenges defined as routes between two or more points, and 2) the player being bound by gravity in a way that makes it possible to use projected graphics to define the routes and add obstacles. We believe that similar interactions and technology could work in other such environments, e.g., BMX and skate parks. Extending the approach to a larger climbing wall with an automatic belay system should also be possible, but poses more challenges as the computer vision needs to work at a longer distance and tolerate the moving belay ropes. The price of projection technology also grows rapidly with the projection area.

In our future work, we intend to continue exploring the possibilities of user-created and procedural content in sport. It would be intriguing to interview climbers and route creators about their motivations to create routes, what makes a good route, and compare the results to research on game level design. Further, if one can derive a set of design guidelines for good routes or gather enough example data, it should be possible to create a computational creativity system for procedural route synthesis.

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