

# Computer-Aided Imagery in Sport and Exercise: A Case Study of Indoor Wall Climbing

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## ABSTRACT

Movement artificial intelligence of simulated humanoid characters has been advancing rapidly through joint efforts of the computer animation, robotics, and machine learning communities. However, practical real-life applications are still rare. We propose applying the technology to mental practice in sports, which we denote as computer-aided imagery (CAI). Imagery, i.e., rehearsing the task in one’s mind, is a difficult cognitive skill that requires accurate mental simulation; we present a novel interactive computational sport simulation for exploring and planning movements and strategies. We utilize a fully physically-based avatar with motion optimization that is not limited by a movement dataset, and customize the avatar with computer vision measurements of user’s body. We evaluate the approach with 20 users in preparing for real-life wall climbing. Our results indicate that the approach is promising and can affect body awareness and feelings of competence. However, more research is needed to achieve accurate enough simulation for both gross-motor body movements and fine-motor control of the myriad ways in which climbers can grasp climbing holds or shapes.

**Keywords:** Computer animation, Motion optimization, Human-computer interaction; sports; exercise, climbing; motivation.

**Index Terms:** H.5.2 [User Interfaces]: User Interfaces—Graphical user interfaces (GUI); J.4. Social and behavioral sciences: Psychology

## 1 INTRODUCTION

Mental imagery is a cognitive skill in which all or part of the senses are used to create or recreate experiences in the mind [26]. In addition to cognitive preparation and performance, imagery has a strong impact on motivation [17]. In this paper, we propose and investigate a Computer-Aided Imagery (CAI) approach for sport and exercise, by which we denote using a digital sport simulation as part of imagery. What separates CAI from traditional sports video games is the degree of realism – building on recent advances in computer animation and robotics (e.g., [6, 16, 25]) we utilize fully physically-based movement not limited to predefined animations, and we customize the simulated athlete with computer vision measurements of the user’s body. We focus on indoor bouldering, a form of climbing that takes place relatively close to the ground on top of a soft landing surface, and does not require special equipment other than climbing shoes. Perhaps due to its approachability, indoor bouldering is a popular and rapidly growing sport; it was also recently approved to the 2020 Tokyo Olympics together with speed and sport climbing [4].

From a scientific research perspective, indoor bouldering provides a multi-faceted field of study. Bouldering routes are short and focus



Figure 1: The user study setup. Left: Real climber climbing a route shown with projected graphics. Right: Screenshot of our CAI application, with a photogrammetry-based 3D model of the climbing wall and a simulated climber that the user can control.

on complex climbing moves that require both strength and coordination. In addition to the obvious physical challenges, bouldering also provides the cognitive challenge of planning/discovering the optimal or at least possible sequence of moves from predefined starting holds to the top hold – this is reflected in how climbers often use the term “bouldering problem” instead of a “bouldering route”. Due to the static environment and modest space requirements, bouldering can also introduce a controlled but still realistic and ecologically valid sport research context in a laboratory environment.

In this paper, our focus is on cognitive/mental sport training; related to this, bouldering is a closed-loop sport in which the required movements are quite slow and performing well demands lots of cognitive processing both beforehand (preparation) and during (feedback) the climbing [21]. Especially in the preparation phase, climbers utilize mental imagery, i.e., imagine themselves climbing on the wall. Thus, bouldering provides a fruitful sport to study how to enhance and utilize human imagery capabilities and how does imagery effect on performance and motivation.

### 1.1 Mental Imagery

Usually, mental imagery involves either visual or kinesthetic senses or their combination. Imagery is widely used and studied among athletes, who use it to practice motor skills, tactics and strategies or prepare themselves for the competitions. Imagery provides a powerful tool, when accompanied with proper physical training. In addition to sports, different forms of imagery enhance human performance in many different contexts such as in work.

Paivio and his colleagues [17] presented an analytical framework that divided imagery into four different dimensions, namely: cognitive, motivational, specific, and general. Based on these four

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dimensions, five distinct forms of imagery can be extracted. Cognitive specific imagery is used to train execution and correction of a specific motor skill such as a free-throw in basketball. Cognitive general imagery is helpful in e.g., strategy execution and development in gymnastic performance, complex dance routines, and planning a route in climbing.

Research on motivational general imagery [5] has divided it to motivational general-mastery, i.e., being mentally tough and confident in a rough situation and motivational general-arousal that is used to control anxiety and stress prior and during competition or an event. Finally, motivational specific imagery is related to outcome goal-oriented responses such as winning and succeeding in competitions. For example, motivational specific imagery has been found to increase adherence to training programs. Current research on imagery has been concentrated on the perspective and angle of the visual imagery [3], the use of different sense modalities [7], and imagery preference in different sports. As elaborated below, imagery studies conducted among rock climbers provide a good background for the current study.

## 1.2 Rock Climbing and Imagery

Although Boyd and Munroe [2] hypothesized that rock climbers would prefer cognitive general imagery to plan and find routes, no significant difference compared to track and field athletes or beginner and advanced climbers were found. However, the study was not designed to measure the actual preparation process of a climbing event but a general preference of the used form of imagery among different sports and skill levels of rock climbers.

Hardy and Callow [7] studied how the sense modality (visual or kinetic) and visual perspective (internal, i.e., 1<sup>st</sup> person or external, i.e., 3<sup>rd</sup> person) of expert climbers' pre-climb imagery impact their performance in two different bouldering routes. First, the climbers had a 15-minutes rehearsal period and then two minutes to use a given perspective and combination of sense modalities to plan the climb. The results showed that external visual imagery combined with kinesthetic imagery yielded significantly better performance. The finding supported the authors' earlier hypothesis [27] that external visual imagery is better in sports in which the form, e.g., body posture and position is important to see "from outside".

Although the authors of previous studies concentrated on the cognitive side of imagery, going through the route beforehand has also strong impact on the climber's motivation. Proper preparation is likely to increase climber's sense of competence and control over the structure of the activity. Such increase in self-determination positively affects the climbing experience by increasing climbers' satisfaction [11].

Another important way that connects imagery to motivation is that it supports climbers' curiosity to solve a "route-puzzle". Cognitive imagery gives climbers a chance to reduce route complexity beforehand and mentally prepare themselves for the oncoming challenges. Taken together, complexity and increased ability to comprehend the route are likely to increase interest towards the route [22].

Furthermore, interest is one of the cornerstones of the intrinsically motivating activities. Both motivational general-mastery and motivational general-arousal forms of imagery are thought to support desire to physically solve the route. Characteristics for motivational imagery in climbing is to see oneself reaching the top, being tough in a hard place or managing anxiety, which all are likely to prepare climber to climb and increase motivation to climb again. One could also think that finding a novel climbing strategy in simulation makes one curious to try the strategy in real life.

In summary, mental imagery is a powerful psychological (i.e., cognitive, emotional, and motivational) tool that has a strong impact on human behavior. On the other hand, imagery is a complex cognitive skill that is difficult or even impossible to utilize for some people [3]. While some lack the ability to reconstruct mental im-

ages, others do not have the knowledge about the optimal use of the skill, e.g., angle, perspective or modalities. The unused potential of imagery provides a great opportunity for psychologically-oriented technology developers.

## 1.3 Technology and Imagery

Already for some time, VR and game technologies have had the ability to immerse the users to whichever environments and contexts. In recent years, the sense of being there created by the technology has reached new heights as stereoscopic 3D and consumer VR technologies have been developed. Although the purpose of such technology has mainly been to entertain users, previous research has found evidence that it has positive impact on both performance and motivation. For example, games such as EA's FIFA football series or guitar hero are not based on a pedagogical curriculum of how to teach game intelligence in football or the art of guitar playing. Nevertheless, they provide users many skills that transfer to their real-life performance [12].

Outside games, simulators have been built to serve training needs and to support human imagery abilities of specific professions, such as airplane piloting. The added value of simulators in training specific skills, motivating and learning to inhibit one's emotions is unquestionable: commercial pilots need to fulfill a certain amount of simulator training per year to keep up their license. In addition, research on virtual human interaction has demonstrated many strong behavioral transfer effects from VR to the real world, such as learning and prosocial behaviors [19]. Finally, VR therapy has been shown to be very effective in e.g., treating phobias and traumas [10].

Regarding sport games and simulations, an additional field of interest in technological research is computer animation, in particular intelligent control algorithms (movement AI) for physically based simulated characters. Following the early seminal work on spacetime optimization by Witkin and Kass [28], recent research has enabled simulated humanoids to move autonomously in real-time and improvise complex movements without needing any predefined animation data [6]. The control methods work with standard physics simulators, which ensures plausible movements biomechanically motivated optimization criteria, such as minimizing the torques exerted on body joints. In this respect, computer animation research has also converged with robotics (e.g., [25]). In the context of CAI and sports, such simulated humanoids can be used to explore and learn about human movement without limiting the exploration by content produced by an animator or through motion capture.

Taken together, psychological research on imagery, and technological research in games, animation, and VR suggest a novel field of research and an untapped opportunity for studying psychological phenomena with games and simulations. Many questions arise from such set-up: What type of imagery, when and how it should be used to enhance performance and motivation? Can we teach right imagery skills through technology or just use such technology to ensure huge amount of repetitions without physical fatigue or to correct moves and body postures of the performers? How does CAI affect intrinsic motivation, inhibition and self-efficacy? Can one utilize VR to boost both tactical understanding and personal skills both in individual and team sports? Above all, what is the added value of CAI on human behavior, performance and experience?

To start finding answers for the above questions, we begin with a simple laboratory experiment that compares two different preparation methods for climbing, namely CAI and traditional imaginary (TI).

## 2 METHODS

### 2.1 Participants and Experimental Design

Included in the climbing experiment were 20 participants ( $n = 6$  females,  $n = 14$  males). The participants were recruited from various places such as Facebook groups and our university's climbing club's

e-mail list. Climbers participating in the study had an approximately three years of previous climbing experience ( $SD = 2.20$ ) and had succeeded in climbing routes of maximum  $6a/b$  difficulty (French grading system). Participants climb approximately once a week ( $M = 1.13$ ,  $SD = 0.77$ ) and their average height is  $178.5\text{cm}$  ( $SD = 7.56$ ), weight  $75.5\text{kg}$  ( $SD = 13.90$ ) and age  $28.7$  years ( $SD = 5.25$ ).

Each participant climbed total of eight routes, with levels of difficulty ranging from  $5a$  to  $6a/b$ . Routes were designed and graded by a professional routesetter and grading was verified by two researchers with climbing experience. We used within subjects with randomized block design to study participants' performance and experience. All the participants climbed four bouldering routes with TI and other four with CAI. The routes were divided into four equal difficulty categories and each participant was prepared a unique set of routes by randomly selecting the routes from each difficulty category. Moreover, the starting treatment (CAI or TI) was altered between participants. This way we controlled learning and fatigue effects and ensured that participants climbed equally difficult routes.

All the routes were projected into  $4 \times 2.7$  meters indoor climbing wall utilizing Augmented Climbing Wall technology (See [9], Figure 1.) Our aim was that that all participants will be able to solve at least some routes, and none or only few will be able to solve them all. In other words, route difficulty was designed to minimize ceiling effects on collected data. The set-up was first beta-tested with three climbers and minor changes to the procedure were made prior to actual user testing.

In the beginning of the experiment, participants were explained the procedure, then they filled in the consent form and their body dimensions were measured with MS Kinect sensor to reproduce a corresponding CAI avatar. After this, the participants were instructed to perform a warm up and explained that they will climb four times with traditional preparation and four with CAI. Those starting with CAI were then introduced to CAI interface. And after an approximately 5 min rehearsing period the first route was introduced to them. A maximum preparation time for each route, both CAI and TI, was approximately 5 min. In both cases the route was projected into the wall and participants could check out the holds but not to touch them. In TI condition, participants were instructed to prepare for the climb as they normally would, using whatever form of imagery they usually prefer. The only restriction was that they couldn't physically touch and feel the holds. This restriction provides a fair comparison to CAI that only provides visual feedback.

After preparation, participants filled in a short survey about their expectations and then they started the climb. Participants had three attempts per route to climb up. After each climb, they filled in another short survey about the climb. After all four climbs belonging to either of the two treatments participants filled in a "treatment-closer" survey. All in all, the experiment lasted approximately two hours after which the participants received two movie tickets.

## 2.2 Measures

Both qualitative and quantitative data related to climbers' background, climbing experience, expectations, and motivation as well as behavioral data related to actual climbing performance were collected. In the end of the experiment, a semi-structured interview was conducted to each participant.

In participants' background, we were interested in their trait curiosity, self-regulatory style, and both imagery ability and preferences. These were collected as control variables for the statistical analysis of other measures. After each preparation phase, we asked how participants perceived the route puzzle, for example its complexity and their own ability to comprehend the route (i.e., curiosity-related measures [22]), their level of confidence to solve the cognitive puzzle, their confidence to physically climb the route all the way up and finally how would they grade the route they just climbed.

Following information about the performance was collected: number of attempts, pass/fail, flash/no flash (i.e., finish a route in one attempt), and the total time spent on the wall. After each climb, the participants evaluated their climbing experience based on their general feeling, level of arousal, valence, both mental and physical fatigue, how well the route met their expectations, post-grade, and motivation to continue climbing/ study. In addition, after each climb they filled in flow-space [24] that considers their evaluated skills in relation to perceived challenge of the route. After the both treatments, participants filled-in a short version of the Intrinsic Motivation Inventory (IMI) [14]. The whole procedure was recorded with a video camera. However, it is beyond the scope of the current study to analyze the video data.

Finally, each participant was interviewed to find out how they perceived and experienced CAI compared to TI. Following themes were covered in the interview: How CAI differs from TI: pros and cons, did they learn something new from CAI, how did CAI effect on comprehension, curiosity and actual climbing performance, how would they prefer utilizing CAI if available, and how would they improve it.

## 2.3 Statistical Analysis

Quantitative data was analyzed using General Linear Model (GLM) repeated measures ANOVA. Performance measures were analyzed with  $\chi^2$  tests. Distinct GLM's for each set of routes in both treatments ( $2 \times 4$ ) were conducted. The inspection of the distributional assumptions (normality and sphericity) crucial for multivariate statistical tests were satisfactory and showed no univariate or multivariate outliers. All the analyses were conducted with SPSS 24.0. Because of the pioneering nature and a rather small sample size, we also present some marginally significant ( $p < 0.08$ ) findings in Section 3.2. In addition, we provide  $\eta^2$  values that show the effect sizes related to marginally significant  $p < 0.08$  results provided.

### 2.3.1 Qualitative Analysis

The interview data was broken into snippets of text, which were assigned codes (Table 1). For example, comments such as "CAI helps to see the whole" and "CAI helps to see the sequence of movements" were assigned the "Understanding route" code. We further used three high-level categories (positive remarks, negative remarks, suggested improvements) to facilitate summarizing the results in Table 1.

## 2.4 CAI Technology

The experiment setup is illustrated in Figure 1. We utilize both an Augmented Climbing Wall [9] setup for displaying routes on a real bouldering wall, and a separate computer with our CAI application that displays a 3D model of the wall and a simulated climber that the participants can control. The humanoid character starts on the ground at T-pose where its hands/feet are free or detached from the wall. The user selects target holds for the character's hands/feet and specifies its chest direction; CAI then produces a physics-based plausible simulation in real-time using our low-level controller. This cycle is repeated until the character reaches the top hold. The following paragraphs explain how the CAI application is built and how one can control the humanoid character through the proposed interface.

**Modeling the Environment:** We used Autodesk ReCap 360 [13] photogrammetry software to create a 3D model of the climbing wall and holds based on pictures. For a large object like our climbing wall with  $2.44\text{m}$  width and  $3.47\text{m}$  height, we needed 50 pictures to create a 3D model with sufficient quality. Our pictures divided the wall into bottom, middle, and top sections. For each section, we photographed the wall from multiple angles, rotating around the vertical axis in a half circle. The 3D model has approximately less than  $1\text{cm}$  inaccuracy in the hold shapes, which should give the user

an opportunity to inspect the holds approximately similar to real life. The participants can freely rotate and zoom the virtual camera.

Building on recent work on climbing AI by Naderi et al. [16], we use Open Dynamic Engine (ODE) [23] to model and simulate the climber's dynamics and interaction with the wall. All movement results from dynamics simulation with intelligent control, without animation data or inverse kinematics that could limit physical realism and movement diversity. Similarly, we model the holds in ODE as a simple ball-and-socket joints, as simulation of finger skeletal structure is not feasible for real-time operation. However, we have extended the hold model by manually annotating the holds with ideal pulling/pushing directions, typically corresponding to the direction from which one can place one's fingers in a cavity or behind a ledge.

**Humanoid Morphology:** To ensure that the participants are likely to be able to copy the simulated movements (e.g., reach a specific hold from a specific pose), we use Microsoft Kinect V2 sensor and SDK [15] to locate each participant's body joints while in T-pose, based on which we adjust the simulated climber's joints and bone lengths. Note that we do not measure and model other aspects of the participants' biomechanics; modeling flexibility and strength is deferred to future work. Together with the simplified climbing hold model, this means that the simulated climber attempts to display a pose that is optimal given the user-defined target holds, but it is up to the user to evaluate whether they really are able to grasp the holds or whether their hands might slip, which greatly depends on a person's finger strength and climbing experience. This was explained to the participants as part of the CAI instructions.

**Low-Level Controller:** Similar to Naderi et al. [16], we use ODE and control particle belief propagation (C-PBP) [6] to control the humanoid character and simulate physically plausible climbing movements. C-PBP is an online black-box sampling-based trajectory optimization method that attempts to find simulation control trajectories that result in movement that minimizes a cost function. Note that to allow the participants to interact with the climber in real-time and with minimal latency, we use the online version of C-PBP [6] as opposed to the offline version which is used in [16], except when both hands are detached from the holds (e.g. when the climber is on the ground). In the latter case, movement is more challenging to optimize and the increased robustness of offline optimization justifies the added computation time.

As opposed to Naderi et al. [16], the user controls the simulated climber with mouse, clicking and dragging on hands and feet to define target holds. Clicking and dragging on the torso defines a target angle for the torso. Pressing enter makes the climber attempt to reach the target holds and angles. Limbs can also be defined as "free", i.e., with no targets, which leaves the AI free to use them for balancing or frictional contacts with the wall.

Once the target holds and torso direction are specified by the user, C-PBP tries to minimize the multi-objective cost function containing the following components:

- Hands/feet distances to the target holds
- Center of mass distance to the wall
- Joint angular distance from a default climbing posture (hanging with arms straight to minimize fatigue)
- Speed of body parts (to overall prefer calm movements)
- Angular distance between the current and target chest direction
- Angular distance between the actual and ideal pulling/pushing direction.

Compared to [16], our cost function is the same, but we add the last term to make the simulated climber position its center of mass

correctly with respect to the holds. In [16] all holds were considered as "jugs" that are easy to grasp from any direction, whereas our real-life wall has holds where one's fingers will slip if pulling from a non-ideal direction.

## 3 RESULTS

### 3.1 User Background

The analysis of the user background measures provides insight for rather stable traits found in the studied sample, namely trait curiosity, self-regulatory style, and both imagery ability and preferences.

Characteristics for the participants in our study was higher values in interest-epistemic curiosity, e.g., diverse exploration and learning something completely new ( $M = 6.25$ ,  $SD = 0.64$ ) compared to deprivation-epistemic curiosity that involves the reduction of uncertainty, specific exploration, and acquiring information that is missing from an existing knowledge set ( $M = 5.14$ ,  $SD = 0.96$ ). Inspection of the self-regulatory styles showed that the participants were highly intrinsically motivated to climb ( $M = 5.91$ ,  $SD = 0.62$ ). Thus, they scored lower in three different forms of external regulations, namely identified regulation ( $M = 4.90$ ,  $SD = 0.99$ ), introjected regulation ( $M = 2.47$ ,  $SD = 1.02$ ) and external regulation ( $M = 2.88$ ,  $SD = 1.34$ ). Finally, participants showed higher visualization abilities in external (3<sup>rd</sup> person) visual images ( $M = 2.40$ ,  $SD = 1.03$ ) compared to internal (1<sup>st</sup> person) visual images ( $M = 1.89$ ,  $SD = 0.65$ ). Participants scored higher even in the kinesthetic imaginary ( $M = 2.00$ ,  $SD = 0.93$ ) compared to that of internal visual imaginary. Although they showed higher ability in external imaginary, participants preferred using internal imaginary moderately more than the internal one.

### 3.2 Preparation

The two preparation methods were experienced differently. Preparation with CAI made participants think and plan more, and thus provided them an extensive angle to a climbing problem. While using CAI, participants considered route more complex ( $F(1, 19) = 12.68$ ,  $p < 0.01$ ,  $\eta^2 = 0.40$ ) and their ability to comprehend it lower compared to their preparation with TI ( $F(1, 19) = 3.61$ ,  $p < 0.08$ ,  $\eta^2 = 0.16$ ). Although the combination of stimulus complexity and ability to comprehend are related to interest towards the stimulus, participants in both conditions considered routes equally interesting.

Different ways in perceiving the route and own abilities before the actual climb resonated with participants' self-confidence as well. When using CAI, the participants were less confident to solve the cognitive challenge provided by the route ( $F(1, 19) = 6.67$ ,  $p < 0.05$ ,  $\eta^2 = 0.26$ ). Prior to climb, they were also less confidence to climb-up the route compared to their confidence when preparing themselves with TI ( $F(1, 19) = 3.45$ ,  $p < 0.08$ ,  $\eta^2 = 0.15$ ). However, the difference in participants' pre-climb confidence did not effect on their evaluations about the grade.

### 3.3 Performance Data

Although the participants had different mind-sets when starting the climb, they performed equally well on the wall in both treatments. Based on the  $\chi^2$  tests, the two different treatments did not differ significantly in the number of attempts (CAI: 1 attempt = 48, 2 attempts = 7, 3 attempts = 25; TI: 1 attempt = 52, 2 attempts = 7, 3 attempts = 21), number of passed routes (CAI = 58, TI = 56), number of flashes (i.e., climb-up for the first attempt (CAI = 51, TI = 48) or total time spent on the wall.

### 3.4 After the Climb

Neither of the two preparation methods effected the post-climb feelings. Differences between CAI and TI in general feeling, arousal and valence were all non-significant. Similarly, differences in both mental and physical fatigue turned out to be non-significant. In

addition, the found pre-climb difference in both perceived route complexity and ability to comprehend the route were non-existent after the climb.

The additional amount of information that forced participants to put more effort on the preparation with CAI affected both participants' confidence and competence after the climb. With CAI, participants considered the route just climbed easier than expected ( $F(1, 19) = 7.69, p < 0.05, \eta^2 = 0.29$ ) and their subjectively evaluated skills higher compared to TI preparation ( $F(1, 19) = 6.33, p < 0.05, \eta^2 = 0.25$ ). However, there were no differences in evaluated grade, motivation to continue the experiment or perceived challenges of the route.

### 3.5 Treatment Closer

After four successive CAI or TI routes, participants found the activity that included both the preparation and the performance on the wall more important and valuable when prepared with TI ( $F(1, 19) = 5.94, p < 0.05, \eta^2 = 0.24$ ). The two different preparation methods did not differ in any other IMI items.

### 3.6 Closing Interview

Table 1 summarizes the closing interview, which brought up both the additional value and suggested improvements of CAI. Participants also provided ideas of how to use CAI technology as part of their own climbing hobby.

The results clearly indicate that CAI supported participants' understanding of both their own body (dimensions, reach) and the route as a whole. In many cases participants mentioned that they usually concentrate on their hands and forget about the feet. Moreover, some participants stated that instead of preparing themselves prior to climb, they go straight to the wall. Thus, CAI made participants to think, plan and prepare themselves systematically for the climb. This is something most participants considered positive and useful, yet a time consuming activity. As seen in the preparation data, deeper preparation decreased pre-climb confidence. We may speculate that those preparing with TI overestimated their abilities and were falsely confident when entering the wall. In any case, the situation was opposite after the climb: deep preparation with CAI increased confidence, own skills and thus sense of competence.

As first-time users, nine participants mentioned that they would have benefited CAI more with a longer period of use. According to participants, the biggest weakness of CAI was related to realism, especially movement. Movement and control were the most often mentioned issues both in negative remarks and suggested improvements. In many cases participants indicated that the avatar could do things that they cannot do and that they can do things that the avatar cannot do. In addition, the neutral and unisex appearance of the avatar lowered the climber-avatar identification process. Thus, another major weakness of CAI was participant's low identification for the avatar. Some participants referred to this issue in suggesting improving the avatar's looks closer to climber.

Part of the realism problem was also holds and grips. Participants argued about the missing detailed information about the holds and pointed out that holds cannot be considered as equal and that bouldering is a fine-motor skill that needs to be integrated to CAI somehow. The current version with on/off holds doesn't support this aspect of bouldering.

Mentions about the possible use of CAI technology revealed that majority of the participants do not want to see the correct solution for the route puzzle but are eager to solve it by themselves instead. In many cases participants compared CAI to an advanced climber who provides hints in tricky route problems; they found it especially effective when teaching beginners or demoing difficult parts of the routes to another climber. In addition, designing, developing and testing new routes were mentioned as possible uses of the CAI technology.

Perhaps, the most remarkable notions about CAI's potential came from a participant who works as a part-time climbing instructor. This participant pointed out the strength of the technology in its capability to introduce a motor skill piece by piece to a novice climber. Being able to cut a complex motor performance into understandable and meaningful pieces is not a trivial task.

## 4 DISCUSSION

We studied a novel CAI approach to support mental preparation for sports performance. We hypothesized that CAI improves both performance and motivation in bouldering. The results showed how CAI alters preparation and what are its weak points that need to be enhanced in the future studies.

Our qualitative data indicates that preparing with CAI forces a climber to think, plan and explore the whole route and own body in more detail. It can be said that CAI brings extensity into climbing experience. In his early psychological writings, James [8] quotes Ewald Hering in describing extensity as an experiential element, which characterizes voluminous, massiveness, and bigness of an experience. Traditionally, climbers at the level of our participants prepare for the climb by just checking few first holds and imagining how their hands interact with the holds. CAI made climbers to think in 3<sup>rd</sup> person, consider their legs and torso in addition to their hands. Using a 3<sup>rd</sup> person visualization is a preferred condition for sports requiring imagery that supports the body form [27].

The results showed that before the climb, such a demanding preparation made participants to consider the route problem more complex and evaluated it more difficult to comprehend and to climb. After the climb, these feelings turned into positive post evaluations of elevated level of own skill, confidence and decreased sense of route difficulty. In other words, CAI increased participants' post-climb feeling of competence, which is considered one of the main factors of intrinsic motivation [20]. Although we will certainly try to revise our simulation to be easier to use and support pre-climb competence as well, it appears safe to conclude that a CAI simulation should rather err on the side of higher difficulty. We believe it would be disastrous to induce false expectations of competence in CAI, leading to a lingering disappointment after the climb, or even hazardous risk-taking.

### 4.1 Possibilities and Benefits

Clear added value of CAI technology is that it guides climbers to focus, plan and explore motor performance in a particular route puzzle in a systematic way. By doing this, people feel more prepared to perform. Preparation with CAI felt cognitively demanding as routes were experienced complex and ability to comprehend them as low. This reaction is natural as new dimensions (3<sup>rd</sup> person, whole route) are introduced in an old and familiar context. After an overwhelming start, climbers are likely to get used to and learn how to best utilize CAI. Thus, in a long run, positive enhancement in both the performance and motivation could be expected. Even in the current form, the study revealed how CAI can positively affect climbing.

Majority of the climbers prefer to solve the route puzzles by themselves, because it is a big part of bouldering. Thus, climbers thought that they would utilize CAI technology in bouldering centers as part of their climbing hobby, mainly as a "route guide" in tricky situations. In addition, CAI was considered a media that helps climbers to communicate, demonstrate and teach new and difficult routes to each other. Teaching novice climbers' new techniques was one of the strongest themes that came out in the final interviews. Moreover, climbers considered CAI to save some energy, because one doesn't have to try everything physically on the wall.

However, we were not able to demonstrate how such an extensive preparation clearly translates into better performance. One reason for not finding support to our hypothesis could have been that such

Table 1: Interview categories and concepts that were mentioned by more than just one participant, i.e.,  $N > 1$

Positive remarks about CAI		Negative remarks about CAI		Suggested improvements	
Category	<i>N</i>	Category	<i>N</i>	Category	<i>N</i>
Understanding body (reach, feet)	17	Realism problem: movement	8	More precise/easy control	13
More systematic, focused, thinking	17	Realism problem: avatar, identifying	7	Hold details	10
Feeling confident	9	Realism problem: difficulty	6	Finger details	7
Understanding route	8	UI problem: visibility	4	Avatar closer to me	6
Easy to try things, understanding errors	4	Realism problem: holds & grip	3	Show beta, alternatives	5
Saving energy	3	Would rather just climb, not plan	3	Scan real route for CAI	4
Easier to visualize	2	CAI problem: remembering the plan	2	Try different body type	3
				See route grade	2

new technology is not adapted very fast. Climbing four routes with a new method are just not enough to turn CAI into one's own new preparation method in complex sport devoting both the mind and the body. Since people have strong habits in preparing themselves for any physical activity including climbing, they need to try and explore novel methods longer to realize the added values of them, and to include them in their preparation routines. This was seen in the lower importance and value evaluations when using CAI.

Another possible explanation for no significant performance differences between our experimental conditions is that it appears nearly impossible to design a set of routes that implements all the following criteria: 1) bringing out the differences between preparation methods, 2) matching the skills of recruited participants, and 3) not requiring too much time per participants. Because we had to allow some variance in the skills of the participants, the routes had to span a range of difficulties to avoid ceiling effects. Assuming that the difference between experimental conditions is small, the range of route difficulties should be densely sampled. However, limiting the user study duration forced us to only have four routes per condition, i.e., rather sparse sampling of difficulties. In the current form, the procedure took approximately two hours, which is quite a maximum for a laboratory experiment.

## 4.2 Challenges

### 4.2.1 Technology Design Problems

User study raised four partly overlapping concerns about the current stage of CAI technology, namely: marking of holds, hand/finger modeling, realism, and climber-avatar identification. Next, we go through each of these and provide some ideas for future development of CAI technology.

Modeling holds, fingers and hand muscles in bouldering software is a very demanding task. We started user-testing with a CAI version that made some compromises about these issues. In the introduction of the user-study, we emphasized our idea that the current version of the CAI was supposed to promote more route exploration and discovery than fine-tuned finger movements on the wall. We also let participants to visually inspect the real wall while exploring it around with CAI. Nevertheless, almost all the climbers mentioned that they would have wanted more information about the holds. Climber quotes such as "All the holds cannot be the same", and "On/off holds do not belong to bouldering" are good examples of the level of detail we missed. This had consequences to experienced realism as well.

Although we customized the simulated avatar with computer vision measurements of the user's body, users wanted more. Climbers introduced us their ideas of transforming their own personal movement bank, personal muscle strengths, and own looks to the avatar. Probably the biggest issue in realism was the mismatch between climbers' own body and avatar's body postures and movement abilities on the wall. One climber said that "Avatar was able to do moves that I couldn't do and I could do moves that the avatar cannot", which summarizes well the level of required details in sports-related

CAIs. It seems that the participants immediately caught up the potential of CAI beyond our exploration/discovering expectations. This could be a minimum requirement (holds, hands/fingers, movement, body dimensions/capabilities, looks) for all future CAI's connecting fine-motor mind-body activities, and a pre-requisite for a proper climber-avatar identification.

Obviously, hand/finger modeling and mind-body connection to movement realism both have an impact on climber-avatar identification. Together with the avatar's generic puppet looks, these had a decreasing effect on the participants' sense of self-presence in CAI. Especially, their sense of proto self-presence was diminished [18], which is created by the sense of physical being based on a neural map of body schema. In high proto self-presence situations, an avatar feels and is treated like an extension of own body. We didn't consider this side of the CAI and ignored a powerful tool that impacts both motivation and performance [1].

Adding detailed holds (including force directions, different value for different holds), finger/hand modeling (individual strength, falling if out of the strength), personalized looks and physical dimensions, and personal movements for the avatar would likely enhance both self-presence and transfer learning from CAI to the real world. With the above specifications, CAI becomes more of a simulator with many parameters to adjust. However, designers should be careful in this line of development and try to keep CAI still playful and usable enough to support a less technically minded climbers' interest.

### 4.2.2 Bouldering as a Fine-Motor Sport

We learned a lot about bouldering during the study process. First, route as a variable is a very complex and demanding entity. Once a route puzzle is solved its meaning changes and interest towards it diminishes. Secondly, as shown, climbers are very aware of their own body and its capabilities. Providing climbers a constrained and faceless avatar and asking them to climb with it is clearly not ideal. Climbing is a fine-motor sport at least after beginner level and climbers expect an avatar to be able to do same moves as they can. On the other hand, an unrealistically strong and skilled avatar is not satisfying either. There is a fine line between a climbing (sport) simulation and an entertainment sport game. Our current version of CAI ended up being somewhere in the middle.

## 4.3 Suggested Improvements

Finally, we review the potential improvements the climbers brought up in the interview. One suggested solution for the hold-marking problem was a Google earth type of zoom-in zoom-out interface that allows seamless camera movement from a 1<sup>st</sup> person to a 3<sup>rd</sup> person view. In a 1<sup>st</sup> person view, climbers can see their hands and the interface provides more information about the hold directions, force required and so on. Obviously, this set-up requires a finite modeling of the holds but the added value is realism that contributes towards better performance. In a 3<sup>rd</sup> person view, the climber gets a holistic view of both the route and the body, thus increasing the extensity of the experience.

Some climbers suggested that the avatar should be projected straight on the wall instead of the screen. This interface would enable natural interaction with the route and its holds. In this scenario, holds should be marked somehow to indicate their value for the climbers. In addition, tuning avatar with different physical, skill and flexibility measures was a widely discussed idea. Climbing with an avatar equipped with adjustable abilities was thought to give a climber new view-point to climbing. Moreover, it was considered an interesting use case to concentrate on the routes and parts of the routes that are weakly handled by the climbers. In such scenarios, climber may train their weaknesses and learn new techniques to utilize in such cases. A climbing competition with a friend was also suggested such that after each climb, the better climber can remove one hold. This again provides climbers a slightly new puzzle to solve.

All the above examples and ideas provide novel and interesting challenges that we will consider in our future work. In addition, understanding these issues will benefit designers and developers of CAI technologies in future.

## 5 CONCLUSION AND FUTURE WORK

We have introduced the computer-aided imagery (CAI) concept and described its first evaluation in a user study about indoor bouldering. The overall objective of the study was to better understand the added value of utilizing movement simulation and AI technology in physical activity and sport contexts. The high-level aim of our work is to tackle the societal problem of low physical activity motivation by means of technology, and to both develop and investigate novel, motivating, and useful technological augmentations for sport and exercise.

We expected to find an effect on both the climbing performance and self-report measures of motivation. The results clearly indicated the added value of utilizing CAI technology. Participants preparing with CAI reported paying more attention to their feet in addition to hands and being more conscious of their bodily dimensions. They also considered themselves more confident and skilled – i.e., competent – in post-climb self-reports. However, it was clear that the participants would have needed to use the technology for a longer period of time in order to get accustomed to it. Moreover, CAI needs to be designed more sport-specifically and personalized to a higher degree. At least in climbing, it remains a technical challenge to accurately simulate and control both full-body movements and the fine details of grasping different shapes.

Our work with CAI and climbing continues. We will revise the technology and system as per the user study feedback, aiming for a longitudinal follow-up study where climbers can use a CAI simulation in their homes for cognitive practice, e.g., while their bodies need to recover from physical training. Our long-term objective is to implement more detailed biomechanical simulation, and expand the range of sports that can be simulated. We aim to gradually move from bouldering and single athlete simulations to multiplayer sports like martial arts and football, also utilizing virtual reality technology. We should also compare the benefits of letting users make decisions and plan actions themselves vs. having an AI coach provide recommendations and model performances.

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