Design of an Exergaming Station for Children with Cerebral Palsy

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ABSTRACT

We report on the design of a novel station supporting the play of exercise video games (exergames) by children with cerebral palsy (CP). The station combines a physical platform allowing children with CP to provide pedaling input into a game, a standard Xbox 360 controller, and algorithms for interpreting the cycling input to improve smoothness and accuracy of gameplay. The station was designed through an iterative and incremental participatory design process involving medical professionals, game designers, computer scientists, kinesiologists, physical therapists, and eight children with CP. It has been tested through observation of its use, through gathering opinions from the children, and through small experimental studies. With our initial design, only three of eight children were capable of playing a cycling-based game; with the final design, seven of eight could cycle effectively, and six reached energy expenditure levels recommended by the American College of Sports Medicine while pedaling unassisted.

Author Keywords

Exergame; exertion interface; video game design; exergaming station; accessibility.

ACM Classification Keywords

H.5.2 [Information Interfaces And Presentation]: User Interfaces – Input devices and strategies;

General Terms

Human Factors, Design.

INTRODUCTION

Cerebral palsy (CP) is a group of disorders affecting the development of movement and posture, causing activity limitations attributed to disturbances in the development of the fetal or infant brain [21]. As children with cerebral palsy become teenagers, they can experience a cycle of deconditioning resulting in deteriorating physical function. Children who walk with the use of a mobility aid (those classified as Gross Motor Function Classification System (GMFCS) level III [11]) show a significant functional decline through adolescence and during the transition to adulthood. This loss of gross motor function in adolescents with CP is multifactorial, but proximal muscle weakness secondary to disuse, poor physical fitness, changes in body composition, limitations in range of motion, spinal misalignment, and pain are significant contributors [3,11].

Exergames, video games whose play requires physical activity, represent a promising way of enabling children with cerebral palsy to perform exercise while having fun. Exergames can be designed to match the children's abilities. They can be played from home, removing the significant logistical difficulties of travelling to a specialized rehabilitation centre. They can be played with others over a network, providing social contact with peers. Experience with a cycling-based exergame for people without motor impairments has found them to be more motivational than traditional exercise, to encourage more vigorous exercise, and to lead to health benefits over a six-week period [24].

The use of Wii Sports and Wii Fit has been reported in an increasing number of studies involving people with motor deficits resulting from CP. Almost uniformly, these have focused on extending range of motion [6] and improving balance [1,7,8]. The Wii system has also been applied to rehabilitation of people with motor impairments resulting from other causes such as stroke [5,23]. However, these studies have focused on rehabilitation therapy, as opposed to physical fitness.

In this paper, we present the results of a design study of an exergaming station suitable for children with Cerebral Palsy. In this study, we addressed the question of how to design a station allowing children with CP to play exergames involving vigorous activity in a safe, convenient and enjoyable manner. The scope of our work includes the physical design of the station and its software interface to

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games. In this paper, we do not consider the design of exergames per se, or the long-term effectiveness of an exergaming program. We carried out the study using iterative design over a six month period, using a collaborative design process involving paediatricians and physiotherapists specializing in CP, kinesiologists, computer scientists and eight children with CP. Our central findings were:

- Custom-designed hardware is required, allowing easy entry and exit from a walker or wheelchair, and stable support while gaming.
- Input provided by an exercise ergometer must be transformed before being sent to a game to enhance smooth and accurate control of an in-game avatar.

The resulting design was highly successful. While only three of eight children with CP who were tested were able to play a pedaling-based game with an initial prototype, seven of eight could play unassisted using the final version. Six of these seven exercised vigorously enough to meet the recommendations of the American College of Sports Medicine (ACSM). The eighth child also met ACSM recommendations, pedalling with the assistance of an adult.

The paper is organized as follows. We first review related approaches. We then discuss the goals and challenges in designing an exergaming station for children with CP. We discuss the design of hardware and the software challenges of interfacing this hardware to games. Finally, we report on methods for using this hardware to accurately and smoothly control an avatar on screen.

RELATED WORK

Active games are digital games where gameplay involves physical activity. Commercial examples include Wii Sports, where players swing their arm to control a tennis racquet, and Dance Dance Revolution, where players must carry out increasingly complicated dance steps. Some active games are designed explicitly to help improve the physical health of their players; these are commonly termed *exergames*. Commercial examples of exergames include Wii Fit and EA Sports Active. Examples from the research domain include personalized exergames [10], Jogging over a Distance [16] and Breakout for Two [17].

The physical hardware supporting exergames follows three main branches. Many games are based around motion-capture hardware such as the Microsoft Kinect and the Wii Remote. Studies of such games are divided as to whether they are sufficiently vigorous to lead to health benefits. For example, Graves et al. have shown that Wii Tennis leads to half the energy expenditure of traditional tennis [9]. A second approach is ubiquitous games, where gameplay involves navigation of the real world [14]. The third approach is based on traditional exercise equipment (or ergometers), such as the commercial PCGamerBike Mini (figure 3) or the CateEye Gamebike. Since this approach is based on equipment intended for exercise, high levels of exertion can be obtained. Warburton et al. have shown that exergames on the GameBike can lead to better exercise adherence and improved health measures versus traditional exercise on a stationary bicycle [24].

Health benefits have been shown to accrue from exergaming. Motivation to perform physical activity has been shown to increase among people without motor impairments [10,20,24] and with motor impairments [7,26]. Additionally, exergames have been successfully applied to the rehabilitation of people with motor impairments. Both custom-designed games [6,18,23] and commercial games [7,22] have been used to help improve upper extremity impairment in children with CP, improve oxygen uptake and maximum work capability in adolescents with spinal cord dysfunction [26], and improve balance in patients with stroke [1,5,8].

Apart from the work of Widman et al. [26], there has been little work on games for improving the cardio-vascular health of people with motor deficits, particularly from CP. What work there is tells at best a mixed story. Graves et al. showed that for people without motor impairment, Wii Sports games played in bursts of 15 minutes or more provide less vigorous exercise than required for health benefits [9]. Hurkmans et al. [12] showed that in a population with CP, sufficient energy expenditure was obtained under similar conditions (but this population was at the highest level of function, mainly GMFCS level II or higher). This allows cautious optimism, but clearly calls for more study.

More disappointingly, home-based interventions based on the Wii have shown sharply declining interest over periods of 12 weeks or more [2,19,22]. Some interventions have shown positive results, but only in the presence of extraordinary support [4,15].

Much of the difficulty is that few Wii/Kinect/Move games require vigorous use of the controller (as with Wii Sports Tennis and Boxing). Popular Wii games such as MarioKart or Zelda that use a controller do not require physical exertion. The limited selection of truly active game styles available for these gaming platforms leads to loss of interest over time. Games based on cycling ergometers are promising as they allow pedaling motions to control an avatar in a game, matching a wide range of game styles.

THE DESIGN CHALLENGE

A successful exergaming station for children with CP needs to address three challenges: the design of the physical apparatus supporting exercise; the interpretation of input from such a device; and the design of the station as a whole to enable exercise that is sufficiently vigorous to lead to health benefits. While these challenges must be solved for any exergaming station, they are exacerbated when designing for children with motor impairments, and failure to solve them represents a significant barrier to adoption of such a system.

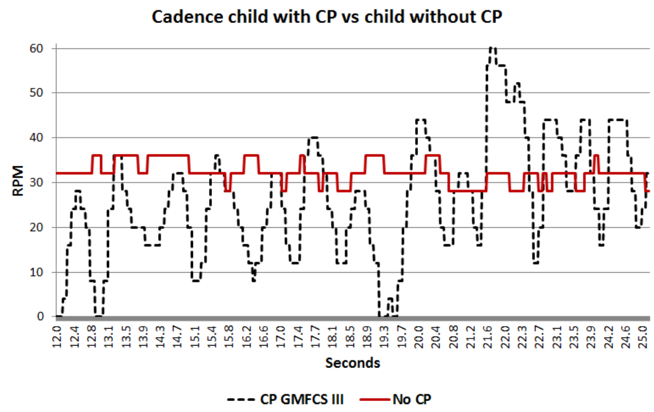

Figure 1. Comparison between typical cadence information of child with CP and child without CP in GMFCS level III pedalling a cycling ergometer

Physical challenge

Children with CP have muscle weakness, reduced range of motion, and poor control over their movements. These aspects of their disability pose difficulties with most existing exergaming infrastructures: many children with CP who use mobility aids have challenges with the finely controlled movement required by Kinect or Wii titles; they cannot balance on a Wii balance board, or sit on a GameBike. As we shall see, these limitations caused us to settle early on a cycling-based device with a custom-designed seat.

The physical station must permit easy transfer from a wheel chair or walker, preferably without the intervention of an adult. This means that children must be able to use their hands to support their weight as they transfer, and there must be no obstacles to impede them as they move. Children with GMFCS level III CP may have poor upper-body strength, and have a hard time supporting their own body while holding a game controller in their hands. Finally, an exergaming station must be sufficiently transportable and compact that it can be installed in a child's bedroom or living room without dominating the space.

Control challenge

Most children with GMFCS level III CP have spasticity and decreased motor control of both their legs. This means that they cannot pedal smoothly. Figure 1 compares the pedalling cadence of a typical child with GMFCS level III CP with that of a typical child without CP. The child with CP has considerably higher variance in cadence. Normally, in pedalling-based exergames, the player powers an avatar with the bicycle. The faster the player pedals, the faster the avatar moves. This literal translation leads to jerky movement of the avatar which is unaesthetic and can hinder typical gameplay tasks such as aiming to stop at a particular location.

The children can use traditional game pads such as an Xbox 360 controller, but their manual ability prevents them from quickly moving between buttons, or from using different controls simultaneously (e.g., pressing a button with one finger while pulling a trigger with another finger on the same hand.) As shown in figure 2, a typical usage involves holding all fingers together and moving them as a unit from button to button.

These issues imply two design constraints. First, pedalling input must be filtered to improve smoothness and accuracy of the movement of an avatar in the game. Second, hand controls must not require rapid hand movements, use of multiple controls at once, or stringently time-sensitive (colloquially "twitch") operation.

Vigour challenge

Finally, the hardware must be designed so that the players are capable of exercising vigorously enough to reach heart rate targets associated with health benefits. For example, the American College of Sports Medicine specifies that 150 minutes per week of moderate activity in 10 minute sessions is sufficient to lead to health benefits [25]. "Moderate activity" is defined as 64%-76% of maximum heart rate.

As we have discussed, exergaming systems for people without motor impairment frequently fail to meet this requirement (although youth with CP GMFCS level III may have lower levels of conditioning, and may therefore require a lower level of activity to raise heart rate). Given the challenges that children with CP face with movement, it is not obvious how to design an exergaming station that supports this level of vigour.

Existing systems do not meet these three design constraints as, being designed for people without motor impairment, they do not solve the physical or control challenges. Worse, they frequently fail to require sufficiently vigorous activity to meet ACSM requirements.

Our research question is therefore whether it is possible to build such a cycling-based exerstation that is safe, usable by people with motor deficits consistent with CP GMFCS level III, and supports exercise at a level of vigor associated with health benefits. To our knowledge, we are the first to address this question.

Figure 2. Child with CP holding Xbox 360 controller

Figure 3. PCGamerBike mini and Xbox 360 controller

DESIGN METHOD

The design constraints identified above led us to favour a custom-designed cycling-based gaming system. For reasons of price and availability of application programming interfaces, we chose the PCGamerBike Mini cycling ergometer and the Xbox 360 game controller (figure 3). From this starting point, we set out to solve: (1) the physical challenge of integrating these controllers into an exercise station suitable for children with CP, (2) the control challenge of interpreting input from the ergometer, and (3) the vigour challenge of ensuring that exercise meets ACSM guidelines.

We followed a participatory, iterative design approach, including eight children with CP, computer scientists, a medical doctor specializing in children with CP, a physiotherapist, and a mechanical engineer. We also received offline advice from a professional game designer, an exercise psychologist, and a kinesiologist.

We held four design and evaluation sessions with the eight children, and an additional experimental session with each child individually. Three children were females and five were males. The mean age was 15.6, with a minimum of 12 and maximum of 18. Five children had spastic diplegia and three had spastic triplegia. Seven of the children were at GMFCS level III and one at GMFCS level IV.

HARDWARE

We experimented with four chair designs. In this section, we summarize the design constraints that emerged through our testing process. This process emphasizes the importance of iterative testing with members of the user group, and the difficulty of anticipating design problems.

We met with eight children with CP through four design sessions, and allowed them to try different alternative designs. We assessed the efficacy of each chair design through observation by a paediatrician and a physiotherapist specializing in CP, and from discussions with the children. We first summarize the four design types, and then summarize our findings. The four chair types are shown in figure 4.

MSS Tilt and Recline Chair: this is a commercial chair designed specifically for children with CP. On paper, it is a perfect match with our requirements: it allows children to sit in a semi-reclined position suitable for recumbent cycling; it provides a stable back and arm rests, and it provides optional straps for holding the child in the chair. Our initial plan was simply to adapt this chair by removing its foot rest and bolting it to a platform where the PCGamerBike mini cycling ergometer was also attached.

However, initial feedback ruled out this design, as the device was perceived as being too specific to people with disabilities. This detracted from the "cool" factor of exercising while playing video games. Moreover, the device was over-engineered for some of the candidate children, some of whom were capable of sitting in standard chairs, and who did not like to be provided with equipment that over-stated the degree of their disability.

Bean bag chair: this chair could be placed against a wall, providing stability while seated. The chair naturally conforms to the body, providing comfort and stability while sitting in a wide range of positions, including the reclined position best suited to recumbent cycling. Furthermore, it is easily portable, and fits well with existing furniture in the home. In initial tests with people without motor impairment, we were excited by the potential of this chair.

In practice, however, it was resoundingly rejected by the youth with CP. They found it uncomfortable being low to the ground, doubted the stability that the chair would provide, and felt a lack of control around chair exit/entry. On the chair's height, children said: "You're more sunk into it… and if you move you get sunk even more", and "Your feet are up… but it makes it feel like your feet are more off the ground. It's more unstable." On entry/exit, one child said "I think the higher it is, the easier it is to sit [down] on it." On stability in general, one stated "I like having an actual chair so I can lean my back against it."

This example emphasizes how misleading experience with people without motor impairment can be in predicting the experience of those with motor impairment.

Customized office chair: Our third chair was a traditional office chair, modified to our specifications by the chair's manufacturer. The original chair was designed for use by police officers. Its arms could easily drop, allowing entry by people wearing firearms. We hypothesized that this would allow the children to more easily enter and exit, as the arms could be dropped on entry, then returned to upright position once the child was seated. The chair was modified to replace its castors with a fixed base and to remove the ability of the chair to swivel.

The chair's drop-arms were successful as predicted, but the chair had too much rotational flex; as one child said, "I found it moved too much". We observed that the chair's soft back impeded pedalling, as some children pushed against the chair back to help them deliver force to the pedals. Interestingly, the children themselves did not report this difficulty, saying for example "I think it has a good back support and it's long enough to support our whole back" and "The fact that it's soft, it doesn't matter for me personally."

Figure 4. Four chair designs: (A) commercial MSS tilt and recline chair, (B) bean bag chair, (C) modified office chair, and (D) custom designed "racer" chair

The children were split on the presence of the arm rests. Some children found the position of the arm rests was incorrect for their physiology, and forced them into an uncomfortable position (e.g., "I prefer when they [the arms] are down.") Others preferred being able to lean on the arm rests, saying "I liked the arm rests so I can lean my elbows", and "It's easier to pedal if there's arm rests on the chair. If I'm supported by the arm rests I think I can go faster."

Racer chair: Our final design iteration was a custom-built platform. The arm rests are flush with the seat, allowing easy entry/exit. The cycling ergometer is attached to the platform, and adjustable for leg length. The seat back is full-height and rigid for stability. The wide attachment for the cycling ergometer does not interfere with the large pedalling attachments.

We found that seven of the eight children were able to pedal without assistance using this device. One initial concern was that the absence of arm rests would be difficult for the children. In practice, some children reported having to work harder to stabilize themselves than with the earlier customized office chair design. We view this as positive, as this self-stabilization provides an additional form of beneficial exercise.

Lessons on Hardware Design

We learned several lessons from this hardware design exercise, which we believe are broadly applicable when designing for people with motor impairment.

We faced considerable logistical difficulties in testing our designs. Even within our small group of eight children, we observed large individual differences. For example, the children were split on their preference of arm rests versus no arm rests on the chair. It is positive that even a small group can provide such a wide range of experience, which highlights the importance of consulting a group at least as large as we did, despite the logistical challenges.

We were surprised by the degree to which we were unable to predict what technologies would work well for children with CP. For example, we believed that the bean bag chair would be successful, but it was met with uniform dislike. This highlights the importance of iterative design grounded by significant testing with the target users.

Another challenge was the difficulty of isolating features of the platform while testing. For example, early problems with the pedals (early versions were loose) had cascading effects on other aspects of the platform.

We saw a significant difference between observed and reported behaviour. For example, all children had difficulty with the padded seat on the custom office chair, but none reported this as a difficulty. Even children who reported problems with the lack of an armrest in the racer chair were in fact able to pedal successfully while using the game controller. This emphasizes the importance of observation, by domain experts such as our medical professionals, in addition to questionnaires and interviews.

CONTROL

The station supports two forms of control: pedaling a cycling-based ergometer propels an avatar in the world, and manipulating buttons and joystick on a controller aims, specifies direction and performs game actions (e.g., jumping or firing a weapon.)

Pedaling Control

Games based on cycling ergometers typically use pedaling to control an avatar. Pedaling faster speeds up the avatar; pedaling slower reduces its speed. Children with CP have difficulty maintaining a smooth pedalling cadence, resulting in problems of *smoothness* and *accuracy* when controlling the avatar. Smoothness is an important aesthetic issue – the avatar should not move in a jerky fashion. Accuracy is important in game tasks where precise positioning of the avatar is important, for example stopping at the foot of a ladder to climb up, or navigating around obstacles. Figure 1 graphs the cadence of a typical child with CP.

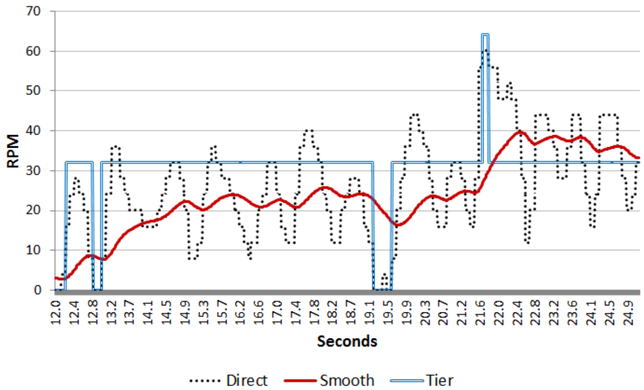

Figure 5. Typical pedaling cadence of a child with CP interpreted via the direct, smooth and tier algorithms.

Smoothing algorithms are broadly employed in video games using handheld controllers [13]. The high variance in cadence of children with CP requires more aggressive smoothing than is typically used. We therefore require a software layer that filters raw cadence information provided by the ergometer into a smoother signal that can be used to modify the avatar's position in a game. We carried out a study to investigate three such algorithms (compared to a fourth control condition). These algorithms are:

1. *Direct Drive* is the control condition where cadence information is transmitted directly to the game.
2. *Smooth:* cadence information is smoothed using a weighted average over a 3 seconds window. This algorithm removes jitter, at the cost of latency.
3. *Tier:* only three game speeds are possible – "stopped", "walking", and "running". This allows considerable variance in cadence while reducing changes in visible speed. The tiers overlap in order to avoid oscillation.
4. *Inchworm:* under this algorithm, the world is divided into a grid of size 1m x 1m blocks (in world units). The avatar remains stationary until the distance to the next block has been pedaled, at which point it jumps to the next block. The avatar is animated to show progress towards the next jump. This algorithm aims to provide excellent accuracy, at the cost of resolution of smoothness in movement.

Figures 5 shows how pedalling input of figure 1 (input from a typical child with GMFCS level 3 CP) is interpreted under the direct, smooth and tier algorithms.

Method

Participants carried out two game-like tasks, one measuring smoothness (variance of in-game speed when the player attempts to move at constant speed) and the other measuring accuracy (players' ability to stop close to the centre of a target). For both tasks, the players used the "racer" bike (described above) and an Xbox 360 controller. Players practiced the task for two minutes. They then performed the task using each of the four algorithms. To balance for order effect, the algorithms were rotated twice according to a balanced Latin square of size = 4, adequate for four conditions and eight participants.

The smoothness task involved pedaling an avatar riding a unicycle while carrying a tray full of eggs in each hand (Figure 6). Players were instructed to pedal as smoothly as they could, so that the avatar could deliver his eggs without dropping any. As the players pedaled, the unicycle wobbled in response to changes in cadence. Players were provided with visual feedback: at every 100 pixels travelled in the game, the variance in cadence over the last two seconds was computed; if it exceeded 10 RPM, an animation showed an egg dropping and a crashing sound was reproduced. The course was 6,000 pixels in length. Variance in pedal cadence was recorded over the course.

The accuracy task was to play the "pipes" game (Figure 7). Players were instructed to pedal their avatar as close to the centre of the pipe door as they could manage, and then push the "A" button on their Xbox 360 controller. For each algorithm, accuracy and time were recorded. Accuracy was measured in pixels from the centre of the pipe, and time was measured in elapsed milliseconds from start of the condition until the player pressed the "A" button.

Results: Smoothness

For the Unicycle game, a within subjects RM-ANOVA was used to determine the effect of each algorithm on player's ability to move the character smoothly through the course.

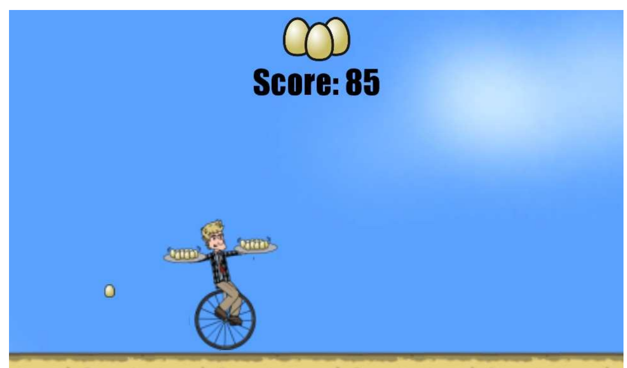

Figure 6. The unicycle game used to measure smoothness. The avatar drops an egg in response to uneven pedaling.

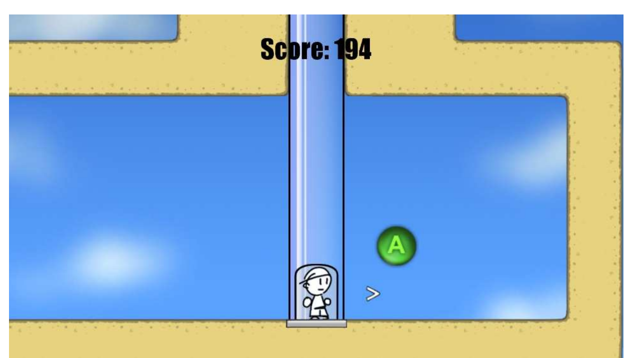

Figure 7. The pipes game used to measure accuracy. Here the avatar is at the center of the pipe door.

We applied Bonferroni correction, giving a significant $p < 0.009$. We found a significant effect of the algorithm on the score ($F(3,21)=45.323$, $p<0.001$, partial $\eta^2=0.866$).

Follow-up pairwise comparisons showed that players' score was higher using the smooth algorithm (M=99.9, SD=0.4) than direct drive (M=65.5, SD=12.5, p<.001), tier (M=82.5, SD=13.8, p=.009) and inchworm (M=52, SD=0.0, p<.001). Additionally, inchworm led to lower scores than tier (p<.001). Direct drive led to higher scores than inchworm (p=.018), and tier led to higher scores than direct drive (p=.015), but both cases are not significant at the level required by Bonferroni correction.

Player comments showed that they found direct drive more difficult than other conditions; one remarked "Are you altering the game? Cause this time it was like... more challenging". One participant noted that the tier algorithm was not responsive to changes in cadence: "I noticed that even though I was pedaling harder, it was always going at the same speed". Two participants commented on the difficulty of playing with inchworm: "I do have a smooth pace but he keeps on dropping eggs", and "It was difficult because he was jerking around".

Results: Accuracy

A within subjects RM-ANOVA was conducted to compare the effect of each of the four tested algorithms on players' ability to accurately navigate to the centre of each pipe. There was a significant effect of the chosen algorithm at the p<.009 level for the three conditions ($F(3,21) = 12.257$, $p < 0.001$, partial $\eta^2=0.636$).

Follow-up pairwise comparisons showed that the inchworm algorithm led to significantly higher accuracy (M=0.0 pixels, SD<0.001) than direct drive (M=9.9 pixels, SD=6.6, p=.004), smooth (M=16.4, SD=11.1, p=.004) and tier (M=13.6, SD=8.6, p=.003). There was no significant difference between the other algorithms.

A RM-ANOVA was also conducted to compare the effect of each of the four algorithms on the time that players spent on the pipes task. Here we found a significant effect of the choice of algorithm on the time (*$F(3,21)=11.583$, $p<0.001$, partial* η^2*$=0.623$)*.

With the smooth algorithm (M=34.3 seconds, SD=12.7), players were significantly slower than with direct drive (M=22.8 seconds, SD=15.0, p=.005), tier (M=21.4, SD=11.5, p=.003) and inchworm (M=15.6, SD=7.1, p=.001).

A linear regression was conducted to determine the correlation between time and score for each algorithm. The inchworm algorithm was excluded because all players received the maximum score. The other algorithms showed a negative correlation (as time increases the distance to the center of the pipe decreases), but none were statistically significant (direct drive: r=0.351, p=0.395. Smooth: r=0.351, p=0.394. Tier: r=0.317, p=0.445).

Participants noticed the effect of the smooth algorithm on latency; one remarked "it slides more than you want him to". Participants commented that inchworm was significantly easier than the other conditions, stating that "it was extremely easy" and "I didn't have fun because I think what was going on this time was automatic, as long as you pedal he will move the same on the floor."

Discussion: Pedaling Control

The choice of algorithm for pedal control requires designers to trade off accuracy, smoothness and responsiveness to changes in speed. The smooth algorithm provided the smoothest input, as evidenced by the highest scores in the unicycle game. However, it also provided the worst accuracy scores and highest times in the pipe game.

Conversely, the inchworm algorithm performed so well in the accuracy task that players complained that the game was too easy. However, this comes at two costs. First, the avatar moves in a sequence of jumps rather than smoothly (as shown by its poor performance in the unicycle game.) Second, entities in the game world must be positioned on a grid corresponding to the algorithm's step size.

The tier algorithm acted as a middle ground, balancing smoothness and accuracy, but not excelling at either.

We conclude that for games that require high accuracy, designers should consider using inchworm, or should redesign the game so that accuracy is less important. While the smooth algorithm is most effective for reducing variance in cycling cadence, for most game situations, its lagged response to changes in cadence outweigh its advantages.

Button and Joystick Control

All eight children were capable of holding and manipulating game controllers similar to that of figure 2, but with significant limitations. Specifically, they had difficulty with time-sensitive manipulation of controller buttons, and found it challenging to manipulate multiple controls concurrently. Some children had difficulty manipulating the controller with two hands, as they used the other hand to support themselves.

The children used a variety of strategies to manipulate the controller. A typical strategy was to use one hand to hold the controller, and the other to manipulate the buttons, joysticks and triggers. Another was to use all four fingers on one hand to manipulate a single button or joystick. Figure 2 shows a child using his right hand to stabilize the controller while manipulating a button with his right thumb, and using the left hand to use a joystick.

The restrictions of CP lead to difficulties manipulating the controller to play many commercial games. Some games require time-sensitive manipulation of the controller's buttons. For example, platformer games such as Ubisoft's Assassin's Creed require the player to run using one control and initiate a jump using another at exactly the right time in order to climb an obstacle. In our exploratory sessions, several of the children found such time-sensitive actions too difficult, and we conclude that games for children with CP should not require them.

Similarly, commercial games frequently require players to rapidly manipulate multiple controls. For example, in Activision's Call of Duty games, players simultaneously use one joystick to control movement speed and direction, another joystick to aim their weapon, and a trigger to fire. We observed that the children typically do not have the manual dexterity to perform such actions concurrently.

In interviews, one child expressed a preference for Sony's PS3 controller, because it is small and allows them to reach all of the buttons without moving their grip. Two others preferred Nintendo's Wii Remote controller because it can be used one-handed, allowing the other hand to be used to support their body while seated on a couch. However this preference extended only to games using the Wii Remote as a traditional controller with buttons and trigger, not as a motion-control device.

In general, the children prefer to have their arms supported while playing, but only when the arm support is flexible and can be customized for comfort.

Despite these findings, all eight children reported attempting to play action-oriented commercial games such as EA's NHL and Activision's Call of Duty at either their own or friends' houses. This highlights the strong desire of the children to overcome the challenges of using these controllers, and their willingness to improvise with complex control schemes.

We summarize with the following lessons for designers: first, for GMFCS level III youth with CP, it is not necessary to develop custom game controllers; stock gaming controllers can be used. However, the control scheme should be simplified over those found in many commercial games. Designers should assume that only one control at a time can be used, and that controls should not be time-sensitive. Where possible, the control scheme should be designed to permit one-handed use.

VIGOUR

The goal of our exergaming station is to enable improved health through exercise. As described earlier, the American College of Sports Medicine recommends that health benefits can occur from as little 10 minute sessions of moderate exercise, as long as it is 150 minutes in total per week [25]. Exercise is considered moderately vigorous if the participant exceeds a threshold of between 64-76% of their maximum heart rate, where the lower threshold value is applicable to people with lower levels of aerobic fitness, as would be the case for our target population.

To see whether children with GMFCS level III CP could achieve this level of exercise intensity using our exergaming station, we asked our eight participants to play a vigorous game while their heart rate was monitored. This activity was performed following the input control study described in the last section.

Participants played a game in which they controlled a spikey ball rolling across the screen. The goal of the game was to roll over (and burst) as many balloons as they could within a two minute period. The game required no strategy; it simply required players to pedal as hard as they could for two minutes.

Before the session, we captured resting heart rate and the participant's age, and then used the Karvonan formula [25] to estimate the participant's maximum heart rate. Heart rate was logged during the two minutes of play using a Polar heart rate monitor worn using a chest strap. Figure 8 shows that seven of eight participants reached the heart rate threshold for moderate exercise intensity, and all eight reached the "warm up" threshold of 40% of maximum heart rate. Seven participants pedaled without assistance. One participant (the single participant at GMFCS level IV) pedaled with assistance of an adult.

The participants reacted positively to the level of exercise, reporting "this is like therapy – I can feel it", "I like it, is difficult, is something I would do for exercise", and "it would push you to go faster. I think it's productive."

While more study is required with longer exercise sessions, this result indicates that the exergaming station can allow the target population to perform exercise at a sufficiently vigorous level to see health benefits.

DISCUSSION

Our biggest lesson from this study was the multi-faceted nature of the design challenges. Building an exergaming station for children with CP required us to address the physical platform itself, the design of the handheld controller, and algorithms for interpreting pedaling input. From our design sessions, we learned that all three aspects of the problem must be solved well in order for the station to work at all. For example, early problems with the pedal support mounts made it impossible to test the pedaling input algorithms. This required an incremental and iterative design process where slow but steady progress was made on all design fronts simultaneously.

Participant	HR max	40%	64%	70%	Achieved HR
1	203	81.2	130	142	**133**
2	206	82.4	132	144	**149**
3	202	80.8	129	141	**177**
4	206	82.4	132	144	**153**
5	208	83.2	133	146	**141**
6	206	82.4	132	144	126
7	204	81.6	131	143	**157**
8	205	82	131	144	**131**

Figure 8. Heart rates achieved using exergaming station

Working with children with CP introduced challenges not seen in traditional participatory design environments. Parents or guardians needed to bring the children to the sessions at the hospital where they took place, sometimes requiring the booking of special vehicles. Because of the demands this placed on the families we were working with, we were restricted in the number and frequency of the sessions. This imposed limitations on the studies we performed. For example, the study on exercise vigour was performed immediately following the study on pedaling input control in order to avoid the need for a second visit. This limited the length of the vigour study, as the children were already tired from the previous study.

There were enormous individual differences between the children. Some could walk with canes, while others required wheelchairs. Some could use an Xbox 360 controller adeptly, while others were significantly challenged. Initially, some could not pedal at all, while others pedaled comfortably. This highlights the importance of dealing with a group that is large enough to be representative of the broader community, despite the logistical difficulties described above.

One way of reducing logistical overhead is the use of interviews rather than direct observation. We observed, however, a significant gap between our participants' self-reporting and their observed capabilities. For example, several participants reported needing arm rests to be able to cycle and use a controller, yet were in fact capable of using the racer bike. All participants reported that they played action-oriented commercial video games, which led us to believe that they were far more adept with game controllers than direct observation showed them to be. Direct observation was therefore critical to gaining an accurate understanding of the participants' capabilities.

Since design sessions were separated by weeks, ongoing testing was difficult. It was not practical to use participants without motor impairment as proxies for children with CP, as their capabilities were too different to lend any predictive value. We found it useful to record input data from the children, and to instrument our games to run in simulation mode, taking recorded rather than live input.

In general, we found it important to separate the design of the exergaming station from the design of the exergames themselves. This approach reduced the risk of conflating problems with the design of the game with those of design of the station, and helped reduce the scope of what proved to be a challenging design problem. Nevertheless, this study did suggest several lessons for game designers:

Avoid "twitch" gameplay: ensure that the game does not rely on time-sensitive actions such as pushing two buttons in quick succession, or operating multiple controls at once.

Avoid the need for accurate positioning or targeting, since the children experience difficulties with accurate movement.

Avoid the need for frequent starts and stops, as some children with CP find it challenging to start pedaling.

Build in customizability, allowing algorithmic parameters to be set at runtime, e.g., to allow easy tuning of the mapping of cadence to in-game speed.

CONCLUSION

In this paper, we have presented the design of an exergaming station for children with CP. The resulting station showed dramatic improvement over early prototypes, allowing seven of eight children tested to pedal effectively within a game, and allowing seven of eight to reach energy expenditure levels recommended by the ACSM. We have identified a series of challenges and tradeoffs in the design of such stations, and have provided practical advice both to designers of the physical apparatus and the software underlying its operation. Our next steps will involve continued design of games for this station, and their evaluation in longitudinal trials.

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