Exertion-Aware Path Generation (Supplementary Material)

WANWAN LI*, George Mason University
BIAO XIE*, University of Massachusetts Boston
YONGQI ZHANG, George Mason University
WALTER MEISS, University of Massachusetts Boston
HAIKUN HUANG, University of Massachusetts Boston
LAP-FAI YU, George Mason University

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1 EXPERIMENTS

1.1 Obstacles

Here is one more example of forbidden zone design. In this case, during optimization, paths will avoid the manually specified obstacle-Armadillo standing in the center of the terrain. Users can specify any bounding area around the Armadillo as the forbidden zone as shown in Figure 1.

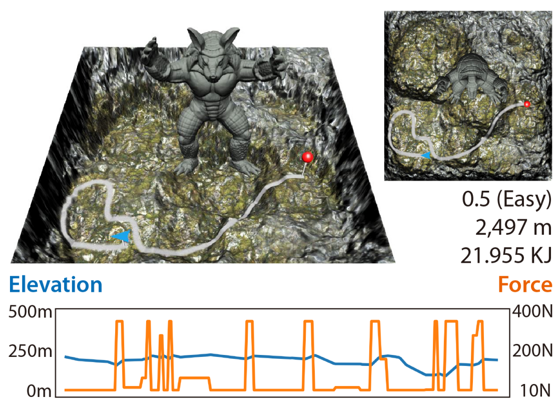

Fig. 1. Paths generated with the avoidance of manually specified obstacles which is an Armadillo in this case.

2 USER STUDY

2.1 Details of Enjoyment Test

To test the enjoyment of biking generated paths using our VR setup, we recruited 23 participants to bike our generated paths. They were university students and staff. They were 23 years old on average and their average body mass index was 23kgm^{-2}. 11 were males, 11 were females, and 1 did not disclose his/her gender.

2.1.1 Procedure. Each participant was briefed about the experiment process and given a warm-up session to get familiar with the bike. Then the participant was asked to ride a generated path (from Section 5.1) in three different exercise modes (VR mode, TV mode and Gym mode) given in a randomized order. In the VR mode, the participant biked while viewing the path via the VR headset. In the TV mode, the participant biked while seeing the game view on a television screen. In the Gym mode, the participant biked while watching some basic information of the current exercising progress like using a regular biking machine in a gym. Note that in all modes the participant used our custom-built bike whose force feedback changed according to the path's elevation angle. After playing each mode, the participant took a 3-minute break. During the break, we asked the participant to fill out a questionnaire about the enjoyment as shown in Table 3.

2.1.2 Results. We examined descriptive statistics on our participants' performance using a Friedman Test to detect if there was an overall difference across the three different modes. We also conducted Wilcoxon signed-rank tests to pinpoint where the difference was located in each pair of modes. (e.g., VR-TV pair).

Figure 2 shows the physical activity enjoyment scale questionnaire (PACES) results. PACES [Kendzierski and DeCarlo 1991] is a quantitative measurement in exercise science to examine one's perceived enjoyment level of exercise activity. We used a modified version [Graves et al. 2010] for our user evaluation. In the Friedman Test, there was a statistically significant difference in average ratings of the three different modes ($\chi^2 = 23.079, p < 0.017$).

A post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.017$ ($\alpha = 0.05$, $n = 3$). The medians (IQR) for the PACES questions across the VR, TV and Gym modes were shown in Figure 2. Significant differences were found in average ratings between VR and TV ($Z = -3.052, p = 0.002$), VR and Gym ($Z = -3.621, p < 0.001$), as well as Gym and TV ($Z = -3.480, p = 0.001$). From the results, we conclude that the participants generally preferred exercising in virtual reality since it was more enjoyable.

*Equal Contributors

Authors' addresses: Wanwan Li and Lap-Fai Yu, Computer Science Department, George Mason University, 4400 University Dr, Fairfax, VA 22030, US.

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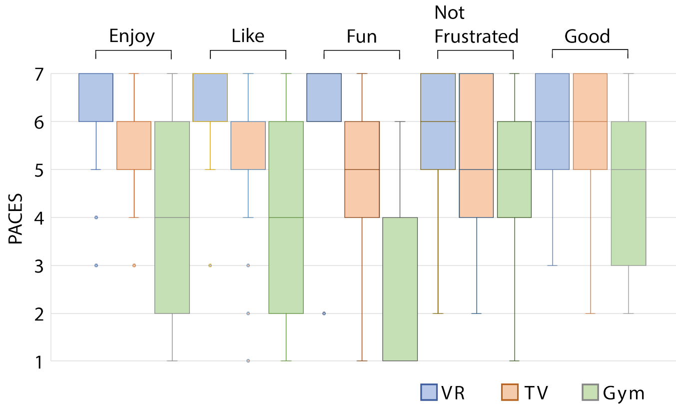
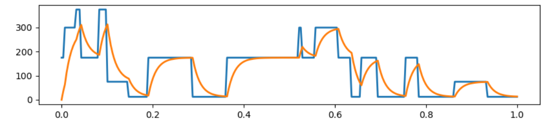
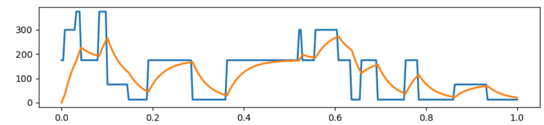


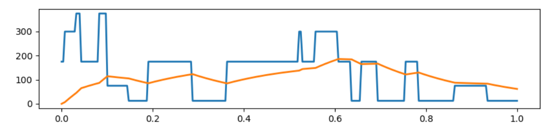
Fig. 2. Enjoyment test. PACES results for different modes.



(a) inertia I_P =5



(b) inertia I_P =10



(c) inertia I_P =50

Fig. 3. Illustration of the inertia effects: Blue curve is the targets power output $P(t)$ from Hard 30kJ. Yellow curve is the predicted power output $p(t)$ using Equation 1 which is closer to the user study result.

2.2 Conversion Between Expected Feedback Force and Expected Power Output Target

As described in Section 4.2 of our main paper, we used the resistance force $f(t)$ to compute the total work cost $C_W(\mathcal{P})$. The resistance force $f(t)$ is formulated in Newton. In our custom-built bike, we obtain feedback power (in watts) from the power meter.

We conducted a trial experiment with 10 participants to obtain conversion between each level of feedback force of our bike and feedback power output. There are six discrete levels of feedback force in our exercise bike. For each feedback level, we asked them to ride the bike with a constant speed of 60 rpm for two minutes. Then we obtained the average power output of that level from a power meter.

Then we can analyze the participants' energy expenditure during the exertion test by comparing their power output results during the entire gameplay with the expected power output targets of the generated paths.

2.3 Additional Details of Demographic Information

2.3.1 Enjoyment Test. We asked our participants to complete a generated path (randomly selected out of *Rocky Hill*, *Terrace Hill*, and *Desert Hill*) under three different exercise modes (VR mode, TV mode and GYM mode) given in a randomized order. Table 1 shows the demographic of our participants.

2.3.2 Exertion Test. Similarly, we asked another group of participants to ride the Hard 15kJ and Hard 30kJ paths of the *Rocky Hill* for an exertion test. Their demographic information is shown in Table 2.

2.4 Additional Analysis of User Study Results

2.4.1 Deviation From Target Power Output in Exertion Test. As described in section 6.2, we observed that overall the results were close to the targets. On average, the energy expenditure for the Hard15kJ path was 17.8kJ and that for the Hard30kJ path was 27.9kJ. In order to explain such slight deviations between the user study result and the specified target, we introduce the concept of inertia of power I_P. By the definition, inertia is a property of matter by which it continues in its existing state and it influences on how much time it takes to change from a current status into a new status. Let users' power output $p(t) = f(t)v(t)$ and $v(t)$ be the velocity of a moving object at time t and $f(t)$ is the feedback force.

From the observations, when the target power output $P(t)$ increases due to a increasing feedback force $f(t)$, a user tends to decrease his velocity $v(t)$ to maintain his current power output $p(t)$, which means, it takes seconds for him to increase the speed back to normal in order to adapt himself into a higher target power output level. Therefore, his power output is lower than expected target power output during this time periods. This explains that the energy expenditure for the Hard-30 path was 27.6kJ which is a little bit lower than the target 30kJ.

Similarly, when the user is riding at a stable velocity $v(t)$, if the target power output decreases as feedback force $f(t)$ decreases, the user tends to increase his velocity to maintain current power output $p(t)$. Thus, his power output is higher than expected target power output $P(t)$ during this periods.This explains that the energy expenditure for the Hard-15 path was 17.8kJ which is a little bit higher than the target 15kJ.

Mathematically, these phenomenon can be easily explained by further exploring the power output's inertia effect. Assuming the value of the power output is a status, then at time t the current power output $p(t)$ is affected by the target power output $P(t)$ through differential equation:

$$\frac{\mathrm{d}p(t)}{\mathrm{d}t} = \frac{P(t) - p(t)}{I_P} \tag{1}$$

where I_P is the inertia of the power output.

Therefore, we validate this assumption by approximating predicted power output $p(t)$ using Equation 1 by setting inertia I_P =5, 10, 50 respectively shown in Figure 3, from the trend of these plots, as the inertia I_P = increases, the power output curve becomes more resistant to the target change and in turn introduces more deviation from the target settings. As matters of fact, our custom-built bike is flexible enough to catch up with target settings so that the deviation

Table 1. Demographic information of participants (Mean (SD)) in the enjoyment test.

Demographic Information	
Average age	23 years old (3)
Gender	Male (47.8%), Female (47.8%) Prefer Not To Say (4%)
Weight (kg)	68.08 (28.398)
Height (cm)	169.8 (10.2)
BMI (kg/m^2)	23.08 (7.19)
Are you an athlete? (e.g., do you do sports regularly?)	Yes (22%), No (78%)
How often do you exercise with an indoor bike (e.g. stationary exercise bike)? 1 = not at all, 5=very often	1.39 (0.7)

Table 2. Demographic information of participants (Mean (SD)) in the exertion test.

Demographic Information	
Average age	26 years old (6)
Gender	Male (60%), Female (40%)
Weight (kg)	60.5 (9.1)
Height (cm)	169.0 (6.6)
BMI (kg/m^2)	21 (3)
Are you an athlete? (e.g. do you play sport regularly?)	Yes (0%), No (100%)
How often do you exercise with an indoor bicycle (e.g. stationary exercise bike)? 1=not at all, 5=very often	1.5 (0.7)
How often do you exercise with an outdoor bicycle (e.g. regular bicycle)? 1=not at all, 5=very often	1.5 (0.8)

is relatively less significant and ignorable. However, our observation can be further studied for reducing the deviation for larger-inertia bike setting-up to produce more accurate exertion-aware path generations.

3 USER FEEDBACK

At the end of our user study experiments, we asked our participant to answer some open response questions. Table 4 shows the answers.

REFERENCES

Lee EF Graves, Nicola D Ridgers, Karen Williams, Gareth Stratton, Greg Atkinson, and Nigel T Cable. 2010. The physiological cost and enjoyment of Wii Fit in adolescents, young adults, and older adults. *Journal of Physical Activity and Health* 7, 3 (2010), 393–401.

Deborah Kendzierski and Kenneth J DeCarlo. 1991. Physical activity enjoyment scale: Two validation studies. *Journal of sport and exercise psychology* 13, 1 (1991), 50–64.

Table 3. PACES items. Please rate how you feel at the moment about the physical activity you have been doing.

1	2	3	4	5	6	7
* I enjoy it						I hate it
1	2	3	4	5	6	7
I dislike it						I like it
1	2	3	4	5	6	7
It's no fun at all						It's a lot of fun
1	2	3	4	5	6	7
*I fell good physically while doing it						I feel bad physically while doing it
1	2	3	4	5	6	7
I am very frustrated by it						I am not at all frustrated by it

*Item is reverse scored (e.g., "7" becomes "1") when we report it in the main paper.

Table 4. Open response answers from our user study experiments.

What feature you like in our game?	**What feature you don't like in our game?**	**Please write down anything else you want to tell us**
VR	bike hardware can be improve	I really enjoy playing VR bike
Visualize the terrain / as the motion of bike	When I stopped, the view is still going	Nice try, may the turning should be that sharp which I feel dash out of the lane
Landscape and bike mechanics	None	Perhaps the angle of the virtual bike should match the road more closely
The environment, the trees and buildings are awesome		It is awesome
Sport	Backgroud	
Exercise	Not really clearly	Take the VR it more fun in this game
Screening quality	Nothing	
The realistic behaviour	In some parts the resolution was not good	Doing the exercise with the VR was way easier that without it or just seeing the image in a VR monitor
More fun for riding bike.	Not friendly with person who wear glasses.	I would like to control the direction and feel actual bumping during the game. Changeable background and maybe add sounds too.
I want this more thant regular exercise bike.		
The feeling is better than bike in gym	The machine is a little heavy	The animation needs to be more fluently
Experience is interesting	Views are same and bike is not comfortable	It's good
up and down is funny, and feels real	Some road there are gaps and feels I would fallen	
Like a rollar coaster		
I am afraid of height. When the bike is descending from the top of the mountain, my heart is pumping very fast.	This exercise bike should implement a brake. When I am riding too fast, unintentionally, I want to using the brake to slow down.	
	The feeling of uphill and downhill	
Let me do exercise	Graphics	