6-2012

ExerLink: Enabling Pervasive Social Exergames with Heterogeneous Exercise Devices

Taiwoo PARK

Inseok HWANG

Uichin LEE

Sunghoon Ivan LEE

Chungkuk YOO

See next page for additional authors

DOI: https://doi.org/10.1145/2307636.2307639

Citation

PARK, Taiwoo; HWANG, Inseok; LEE, Uichin; LEE, Sunghoon Ivan; YOO, Chungkuk; LEE, Youngki; JANG, Hyukjae; CHOE, Sungwon Peter; PARK, Souneil; and SONG, Junehwa. ExerLink: Enabling Pervasive Social Exergames with Heterogeneous Exercise Devices. (2012). *MobiSys'12: Proceedings of the 10th International Conference on Mobile Systems, Applications, and Services, June 25-29, 2012, Low Wood Bay, Lake District, UK*. 15-28. Research Collection School Of Information Systems.
Available at: https://ink.library.smu.edu.sg/sis_research/2075

Author
Taiwoo PARK, Inseok HWANG, Uichin LEE, Sunghoon Ivan LEE, Chungkuk YOO, Youngki LEE, Hyukjae JANG, Sungwon Peter CHOE, Souneil PARK, and Junehwa SONG

ExerLink - Enabling Pervasive Social Exergames with Heterogeneous Exercise Devices

Taiwoo Park, Inseok Hwang, Uichin Lee†, Sunghoon Ivan Lee‡, Chungkuk Yoo, Youngki Lee, Hyukjae Jang, Sungwon Peter Choe, Souneil Park and Junehwa Song

Department of Computer Science, KAIST, †Department of Knowledge Service Engineering, KAIST and ‡Computer Science Department, UCLA

{twpark, inseok, chungkuk, youngki, hjjang, sungwon, spark, junesong}@nclab.kaist.ac.kr, †uclee@kaist.edu, ‡silee@cs.ucla.edu

ABSTRACT

We envision that diverse social exercising games, or exergames, will emerge, featuring much richer interactivity with immersive game play experiences. Further, the recent advances of mobile devices and wireless networking will make such social engagement more pervasive—people carry portable exergame devices (e.g., jump ropes) and interact with remote users anytime, anywhere. Towards this goal, we explore the potential of using heterogeneous exercise devices as game controllers for a multi-player social exergame; e.g., playing a boat paddling game with two remote exercisers (one with a jump rope, and the other with a treadmill). In this paper, we propose a novel platform called ExerLink that converts exercise intensity to game inputs and intelligently balances intensity/delay variations for fair game play experiences. We report the design considerations and guidelines obtained from the design and development processes of game controllers. We validate the efficacy of game controllers and demonstrate the feasibility of social exergames with heterogeneous exercise devices via extensive human subject studies.

Categories and Subject Descriptors

C.3 [**Special-purpose and Application-based Systems**]: Real-time and embedded systems; H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*evaluation/ methodology, input devices and strategies, prototyping*

General Terms

Design, Human Factors, Experimentation

Keywords

Exergame, Exercise, Social, Pervasive, Heterogeneous

MobiSys'12, June 25–29, 2012, Low Wood Bay, Lake District, UK.

1. INTRODUCTION

Applying diverse pervasive devices to game interfaces opens up many opportunities for game developers to interweave real world activities into the virtual world fabric of games. One promising application domain is exergaming that combines exercise and gaming to provide positive and engaging fitness experiences [6, 10, 4, 45].

More importantly, we envision that *pervasive* social exergames supporting multiple exercise modalities will enable true ubiquitous social interactions, fostering social bonds and friendships. Further, such exergames will allow people with different exercising capabilities and preferences to gather from diverse situations and to play/exercise together. For instance, a homemaker running on a treadmill at home, a son who is a college student cycling in his school gym, the husband on a business trip using his jump rope, and a young daughter using a hula hoop at her friend's house can all meet virtually and exercise together over a multi-exercise game. They will be able to choose the right exercise appropriate for their given situation or preference, enjoying exercising together via social exergames.

In this paper, we explore the potential of using multiple exercise devices as game controllers and incorporating multiple heterogeneous controllers into a game. Specifically, we consider a class of exercise equipment used for repetitive, individual, and aerobic (RIA) exercises such as treadmill running, stationary cycling, hula hooping, and jump roping. RIA exercises are widely performed by many people, largely because RIA exercises are simple and easy to learn and bring positive effects to physical health [21].

However, realizing an interactive multi-player exergame using RIA exercise devices as game controllers gives rise to important challenges resulting from the differences between exercise modalities, e.g., rotating ropes and taking steps. First, converting exercise devices into game controllers requires exercise-specific considerations of sensor hardware and software support to acquire the exercise intensity metrics to be used as game inputs, e.g., exercise speeds. Traditionally such support has been provided only for specific types of exercise equipment such as stationary bikes. Second, it may cause significant imbalances in game performance among game players who simultaneously utilize different types of controllers designed for different exercises. While imbalance due to network delay/jitter has been well investigated in the literature [16, 29, 18], little study has been done to understand the performance difference with heterogeneous exercise devices and personal preferences/capabilities which is a unique problem in pervasive social exergames.

In this paper, we propose the ExerLink platform featuring conversion and balancing mechanisms that are carefully tuned through an iterative design process including a series of field trials. ExerLink aims to deliver fair game play experiences by considering the unique aspects of social exergames. The main contributions of this paper are summarized as follows. First, we explore the possibility of incorporating different exercises into an interactive exergame and propose novel balancing mechanisms that consider heterogeneity of exercise devices and personal differences in capabilities and preferences. Second, we provide design considerations and guidelines obtained from the design and development processes for four game controllers. The conversions have been thoughtfully crafted over eight months of iterations incorporating three preliminary user tests. Third, we use an interactive game called Swan Boat [6] over ExerLink to demonstrate the feasibility of a pervasive multi-exercise game in co-located and remote environments. We also report the unique patterns of social interactions in this multi-exercise game.

The rest of this paper is organized as follows. In Section 2, we provide a brief summary of background and motivation. In Section 3, we present the key design issues and overview the platform architecture. In Section 4, we illustrate the conversion and balancing mechanisms that aim to deliver fair game play experiences. In Section 5, we detail how we build exercise-game controller prototypes using existing equipment (e.g., hula hoops, interactive treadmills). In Section 6, we perform a human subject study to evaluate the performance of exercise-game controllers. In Section 7, we conduct two case studies to evaluate the proposed balancing mechanisms and to understand social interaction patterns in both co-located and remote play. In Section 8, we discuss the limitations of the current work and describe future research directions. Finally, we present the related work in Section 9 and conclude the paper in Section 10.

2. BACKGROUND AND MOTIVATION

2.1 Why Social Exergames?

One of the main goals of exergaming is to encourage physical activity as it can transform tedious exercise into an enjoyable experience. This approach complements existing persuasive techniques that rely on peer pressure and social recognition. For instance, in Fish'n'Steps [28], an exercise logging application using a pedometer, a user raises a virtual fish that grows according to the number of steps its owner takes. In Houston [14], users can check each other's exercise records and exchange comments using text messages. Kukini, an extended version of Nike+iPod [10] supports social interactions by allowing users to share exercise results.

Beyond encouraging physical activities, recent literature also showed that due to their rich interactive nature, exergames can be used to foster social bonds and friendships. For instance, Wii Sports [5] provides social game play experiences mostly in a co-located place. Gamebike [3] allows individuals riding stationary bikes to compete with each other in a virtual race. Muller et al. [39] explored the relationship between social interactions and physical activities through their own work *Table Tennis for Three* and further showed that remote exergames bring similar social benefits based on their remote jogging game called *Jogging over a Distance* [39]. While the benefits of social exergames are well documented, existing approaches cannot be fully extended to *pervasive* social exergame scenarios because players must visit gyms and use designated equipment regardless of their preferences or physical abilities. Our goal is to relax this restriction such that users with portable exercise devices can join social exergames anytime, anywhere and those users with heterogeneous devices can enjoy the same social exergames with a fair game experience.

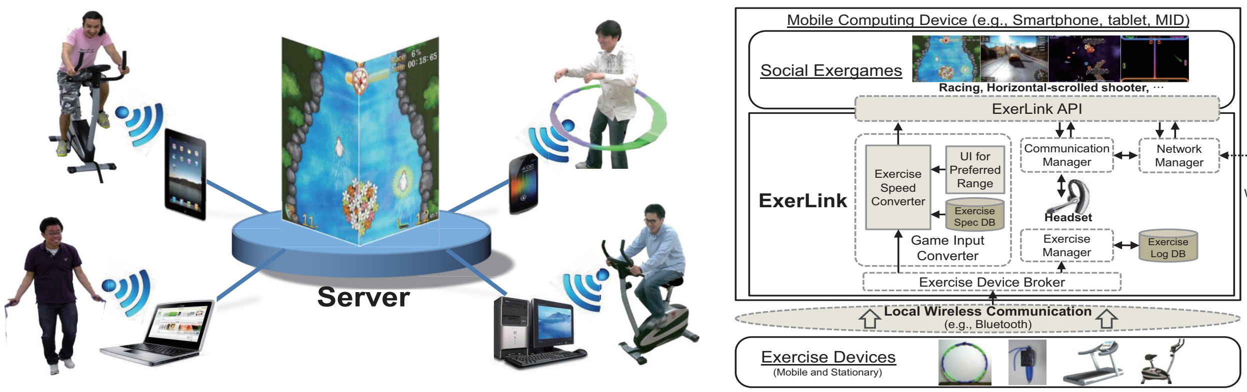
2.2 Motivating Scenario

Jessica, a 31-year-old woman working at a sales department, has gradually gained weight over the past couple years. She tried a few different forms of exercises, but she failed to lose weight because she felt that exercising is not so enjoyable. Moreover, due to the nature of her career, she often travels across town for sales, and it is very difficult to consistently visit exercising facilities. She found that two of her close friends, Christine and Nicole, had the same problem, and they decided to use ExerLink to make exercising more enjoyable. Jessica wants to exercise on a treadmill or jump rope because her major objective is to burn calories. On the other hand, Nicole prefers hula hooping because her objective is to strengthen her abdominal muscles and Christine prefers to ride an exercise bike due to her knee problem. At 6 PM everyday, they either meet up at the gym or remotely join the group at their own houses to exercise. One day Jessica has to visit the other side of the town. Fortunately, she doesn't have to worry because she can bring a jump rope and join the group exercise remotely using her smartphone. As a result, Jessica and her colleagues are able to consistently participate in the group exercise, and continue to lose weight for the next several months.

2.3 Repetitive-Individual-Aerobic (RIA) Exercises

We consider repetitive, individual, and aerobic exercises such as treadmill running, stationary cycling, hula hooping, jump roping, etc. These repetitive-individual-aerobic (RIA) exercises are suitable for use in multiplayer exergames due to their intrinsic characteristics as follows:

- **Popularity**: They are popular among many people of all different age groups, largely due to positive effects on physical health [21].
- **Ease of access**: They are usually simple and easy to learn and perform.
- **Monotony**: The solitary and monotonous nature of RIA exercises provides strong motivation to create games to relieve the monotony.
- **Long-lasting**: Aerobic exercises are usually performed for a long enough time to play a game as compared to anaerobic exercises.
- **Measurability**: By measuring the degree of repetitive intensity while exercising, we can easily employ exercise metrics as game input. Namely, the RIA exercise equipment can be viewed as 1-dimensional game controllers.



(a) (b)

Figure 1: (a) Team playing a game on ExerLink (b) Architecture overview of the system

2.4 Target Social Exergames

As RIA exercise devices can be regarded as 1-dimensional game controllers, we search for some popular types of games whose core mechanics largely depend on 1-dimensional control, namely racing and vertical position-oriented games. In racing games, players' exercise intensities can be easily mapped to the avatar's speed, as instantiated in several exergames [6, 19, 45]. In vertical position-oriented games such as horizontally-scrolled shooters and paddle games, it is natural and intuitive to control the vertical position of a game avatar using players' exercise speeds.

3. EXERLINK PLATFORM DESIGN

3.1 Design Considerations

Exercise- and Player-specific differences: In our scenario, users could play a game using heterogeneous types of exercise devices at the same time. Moreover, users have different preferences on the range of exercise intensity, according to personal physical ability or purpose of exercise. For example, Jessica may want to walk within 7 km/h as she has a cardiovascular problem or aims to lose her weight more effectively, whereas her friend George wants to run faster than 9 km/h. To cope with diverse needs, the platform should be designed to support different types of exercise devices to be used in one game, as well as to capture users' preferred ranges of exercise intensity. Most importantly, in such cases the game (and its supporting platform) should provide a fair game experience to all users.

Network latency: High network latency would result in a poor game experience, particularly when users are playing over cellular networks [36]. Social exergames should provide effective ways to mitigate the delay/jitter effects on the game play experience in terms of smoothness and fairness.

Interaction modalities: As one of the goals of social exergames is to foster social bonds, the platform should provide rich interaction modalities among users. Building social bonds is one of the strengths of co-located play, as participants can talk to each other or even just glance at each other. In remote game play scenarios, the platform should support some means of computer-supported communications (e.g., voice, video) to effectively facilitate interaction among players.

Exercise history information: It is important to provide users with a summary of exercise performed, such as duration and total calories burned, because it can be used in many useful ways; e.g., logged personally, shared with others, and utilized for setting up further exercise plans. The platform should collect exercise information during game play and provide summary information to the exercisers.

3.2 Architecture Overview

ExerLink mediates social exergames and diverse RIA exercise devices (see Figure 1) and supports mobile devices including smartphones, tablets and Mobile Internet Devices (MIDs). ExerLink provides a run-time environment for game applications, and it is capable of running multiple exergames at the same time. The ExerLink platform processes exercise intensity information from devices and converts it into game input values. The conversion process considers the heterogeneity of exercise devices and personal differences in physical abilities and preferences. The platform mediates communication between game applications and a game server considering the different network delays among remote game players. It also provides a voice communication channel between game players to support social interactions in a remote play situation. Lastly, it tracks and summarizes the amount of exercise performed by players to help maintain the motivation of the players.

ExerLink consists of four key components: the *Game Input Converter*, the *Voice Channel Manager*, the *Network Manager*, and the *Exercise Information Manager*. The Game Input Converter is responsible for translating exercising speeds from exercise devices into game inputs. Specifically, it considers the heterogeneity of exercise devices and users' preferred exercise intensities to provide fair game play experiences. The Voice Channel Manager supports voice communications to facilitate social interactions during game play. It selectively supports various modes of communications on-demand, namely peer-to-peer, team, and all-player communications. The Network Manager supports communication between game applications and a game server while effectively minimizing unfairness in game play due to network delay variation among players, as shown later in Section 4.3. The Exercise Information Manager summarizes exercise statistics. It automatically calculates the energy cost of physical activities from exercising speed in units of metabolic equivalent (MET), utilizing speed-MET mappings such as those described by the Compendium of Physical Activities (CPA) [7].[1] This makes more sense than direct measurement of energy costs, as carrying and wearing measurement devices such as heartbeat sensors can additionally burden users.

4. PROVIDING FAIR GAMEPLAY

To provide fair game experiences, ExerLink considers the following unique aspects of social exergames: (1) significant intensity variation among different exercise devices (e.g., hula hoop vs. jump rope), (2) differences in users' preferred exercise intensities (e.g., preferring slow jumping to fast jumping), and (3) differences in network delay due to heterogeneous network conditions while playing social exergames over the Internet. In this section, we present the conversion and balancing mechanisms which were carefully tuned through an iterative design process including preliminary field trials.

4.1 Converting Exercise Intensity into Game Input

As shown below, a user's exercise intensity using a certain device can be measured using standard metrics, e.g., rotations per minute (RPM) for hula hoops, jump ropes, and stationary bikes, or speed (km/h) for treadmills. We propose a model that converts exercise-specific intensity to game-specific input data. Establishing such a model is nontrivial and requires careful consideration of the exercise type and the individual's preference. In the following, we discuss standard strategies of converting exercise intensity values to game values and then propose a mapping method for social exergames that considers the heterogeneity of exercise devices and individuals' preferences.

4.1.1 Converting Strategies: Throttling and Adjusting

In the field of game design, two distinct strategies are widely used to convert exercise intensity to game input data, namely throttling and adjusting. The concept of throttling is analogous to a throttle lever; each position of the throttle lever uniquely corresponds to some value. Players can easily relate exercise intensity to game value because exercise intensity is proportional to the game input value. For example, when the throttling strategy is adopted in a game using a treadmill as the primary controller, the game input values would be proportional to the player's running speed.

In the adjusting strategy, the player's input acts like a first-derivative that changes the game state, e.g., an acceleration or deceleration control button. For instance, a vehicle keeps increasing its speed as long as the acceleration button is on, and it maintains its current speed when the button is off. In the example of the treadmill-controlled game as above, the game would maintain the current game state if the player keeps running within a predefined speed range which is considered as 'cruise,' similarly to the case of 'no button is on' in the previous vehicle example. If the player's running speed exceeds that range, the game state changes to the acceleration mode; if it falls below that range, it changes to the deceleration mode. The adjusting strategy is very different from the throttling strategy in that running at a given speed does not uniquely determine the game state; it only determines whether the game state changes or is maintained. Note that both strategies work well in practice, and the choice of strategy depends on the game type. In our prototype implementation, we design a multi-player social exergame where throttling is used as the default converting strategy.

4.1.2 Personalized Mapping Mechanism

To enable exercise- and player-specific intensities to take effect in games, we design a personalized mapping function for each exercise device, which converts the intensities into game input values. Those mapping functions are designed in thoughtful consideration of the following unique aspects of social exergames, which we learned over iterative studies on users and different exercise devices.

Ease of Control: Players expect ease of control for game play. For example, suppose that the RPMs of the hula hoop are mapped to the vertical position of a game avatar. The major range of the avatar's positions required by the game should be reachable by the RPM ranges in which the player can hula-hoop naturally, without putting too much effort. If the player is required to change the speed of hula-hoop to either too high or too low value frequently, the player will blame the controller for its lack of controllability.

Consistent Movement: Interestingly, players are quite sensitive to inflection points of movement patterns. An inflection point is a certain point on the intensity curve of an exercise; crossing the point naturally involves the change of the exercise mode. In the treadmill, for instance, an inflection point is around 7 km/h where the mode of exercise is switched between walking and running. Raising the speed of jump-roping over 170 RPM requires players to change their jumping method to alternating their feet or doing double-unders. During our iterative system design, we identified the existence of inflection points in several types of exercises. More importantly, we observed that controlling a game across such an inflection point incurs poor gaming experiences like unintended abrupt motions of the avatar in a game.

Marginal Range: From the two considerations previously discussed, we can define a preferred range for a player, in which the player can change the exercise intensity easily and smoothly. Another important consideration is that, even if the player's input goes out of the one of the two ends of the preferred range, it is desirable for the game to respond to the player's input to some extent. It may be analogous to the "bouncing effect" in iPhones or iPads, which is a gentle implication to let the user know that he/she has scrolled the page to the very end. If the game is designed to suddenly ignore the user's input as soon as it goes just above or below the preferred range, the player would complain that the game controller is unresponsive. To this reason, we need to design "marginal ranges" at the both ends of the preferred range where the responsiveness gradually becomes blunt, so that the players can naturally feel that they are getting out of the preferred range.

Given these observations, we introduce two types of ranges, namely preferred and marginal ranges. The pre-

[1]MET represents the energy cost of physical activities. It is approximately equal to the energy cost of the activity, expressed as kilocalories per hour per kilogram of body weight.

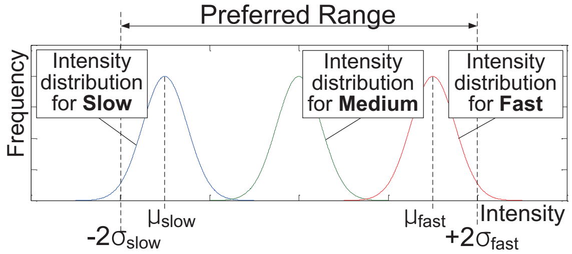


Figure 2: Conceptual overview of personalized mapping

ferred range is determined during the training phase on a per-player, per-exercise basis.

1. The system instructs the user to use an exercise device in three different representative intensities, namely slow, medium, and fast modes. We let the player to determine the preferred intensities for slow, medium, or fast, as we intend the mapping functions to be tuned subjectively to each player.

2. We determined the minimum and the maximum values of the preferred range based on the measured intensity distributions of the players. To be specific, we first observed that the players' intensity distributions roughly follow the normal distributions. Then we define the preferred range to include two-time standard-deviation intervals around the means of each mode, as shown in Figure 2. Accordingly, the preferred range for player i is defined by its minimum and maximum values as the following.

$$min_i = \mu_{slow} - 2\sigma_{slow}$$
$$max_i = \mu_{fast} + 2\sigma_{fast}$$

   where σ_{slow} and σ_{fast} are the standard deviations of intensity samples from slow and fast modes, respectively and μ_{slow} and μ_{fast} are the means of the samples from the modes, respectively.

3. Importantly, the preferred range should be defined not to include an inflection point in the middle, so as not to negatively affect the gaming experience as described above.

To summarize, for a given exercise, a player's preferred range captures a continuous, inflection-free range of the exercise intensities over which the player can change their exercise intensities without much difficulty. For instance, if a user decides to use a jump rope as a game controller, she simply goes through the training phase, and the preferred range is configured accordingly (e.g., from 120 to 140 RPM).

Besides, the marginal ranges are placed at both ends of the preferred range, namely lower and upper marginal ranges, respectively. In the case of a jump rope, the lower marginal range corresponds to [0, 120), and the upper marginal range corresponds to (140, R^{jr}_{max}) where R^{jr}_{max} is the maximum achievable RPM of jump-roping. We then need to determine the game value range for both preferred and marginal ranges. In our design, we empirically assign the preferred range to be mapped to the range of 20% to 80% of the game value (i.e., total 60% of the game value). The lower marginal range takes the lower 20% of the game value, and the upper range takes the upper 20% of the game value. As illustrated in

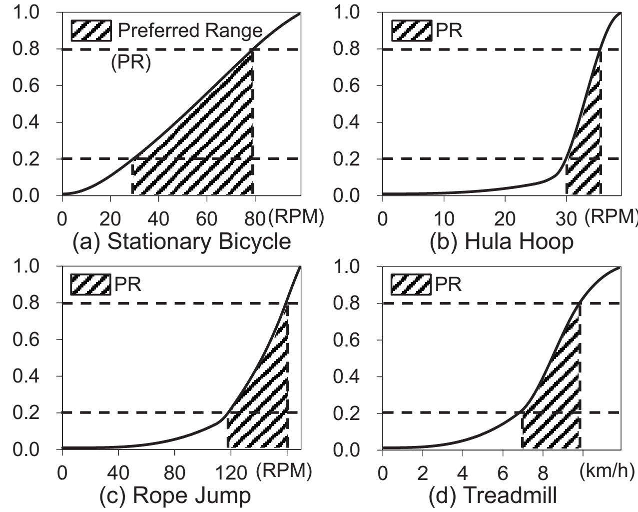


Figure 3: Examples of mapping functions for RIA controllers. The horizontal axis of each figure represents the exercise intensity of the exercise. A player has a unique Preferred Range (PR) for each device. The game input value range of 20-80% is used to map PR, and the remaining ranges (0-20% and 80-100%) are used to map Marginal Ranges (MRs). A mapping function is defined by connecting the four points shown in the graph.

Figure 3, we construct a resulting mapping function using a Bezier curve connecting the following points, namely (0, 0), (X_{min}, 20%), (X_{max}, 80%), and (R^k_{max}, 100%). Here, a player's preferred range is [X_{min}, X_{max}], and the maximum achievable exercise intensity of device k is R^k_{max}.

4.2 Balancing Heterogeneity

We present a scheme for balancing heterogeneity for fair and collaborative game play. For the sake of illustration, we use a multi-player game called Swan Boat [6]. In Swan Boat, we have a team of two players exercising in close harmony with one another to collaboratively control the direction of a boat.[2] The difference in exercise intensity between team members determines the direction of their boat (either left or right). If the intensity levels of both users are the same, the boat moves straight; otherwise, it slants towards the side with higher intensity, with the angle proportional to the intensity difference. As illustrated earlier, our target games are 1-dimensional, and thus, they should not require any additional controllers apart from its core mechanism; i.e., an object is steered using exercise intensity in one direction. To use both directions, the game must restrict a team of two users to control the object or incorporate additional features (e.g., automatically changing direction after reaching at a certain point in 1-dimensional space). In this example game, players should closely collaborate in a synchronized manner, and thus, we expect that they can feel imbalances, particularly when heterogeneous devices are used, or/and their physical capabilities or preferences are different.

How fast one player can steer the boat toward one direction is related to the *movement time*, i.e., the rate of exercise intensity changes, with the exercise device that the

[2] As shown later, two teams can compete with one another to win a boat race.

```
Function : AccelerationBalancing
Input    : Vin is the original game input, t is current time, β is the target rate
Output   : Vout is the converted game input
1.  // detect acceleration
2.  if ((Vin − Vin_old) / (t − t_old) > acceleration_threshold)
3.      if (current_state != ACCELERATING)
4.          current_state ← ACCELERATING
5.          t_accel_begin ← t_old
6.          Vin_accel_begin ← Vin_old
7.      // convert acceleration rate from the beginning of the current acceleration
8.      current_accel ← (Vin − Vin_accel_begin) / (t − t_accel_begin)
9.      converted_accel ← β · current_accel
10. else
11.     if (current_state == ACCELERATING)
12.         current_state ← ACCEL_END_WAIT
13. if (current_state == ACCELERATING || current_state == ACCEL_END_WAIT)
14.     Vout ← Vout_old + converted_accel × (t − t_old)
15. Vin_old ← Vin
16. Vout_old ← Vout
17. t_old ← t
```

Figure 4: Pseudo code of the acceleration balancing. The deceleration balancing can be done similarly.

player is manipulating. Thus, the heterogeneity of devices or player's capability/preference is directly related to the movement time, and this imbalance directly affects the fairness of a game. For instance, a player on the bike can quickly ramp up its speed, whereas a player with the hula hoop can only slowly increase its speed. Given that a player's exercise intensity distribution falls mostly within the preferred range, we consider this range for balancing heterogeneity. The movement time is mainly dependent on a player's preferred range and minimum/maximum acceleration, which are measured during the training phase. For a given set of players and their exercise devices currently in use, we can set the target movement rate through which all players' movement rates are normalized. In our design, we set the target rates by averaging the rates of all players. Here, the acceleration and deceleration rates are inversely proportional to the movement times of upward and downward directions, respectively. We then adjust the acceleration and deceleration rates of each user to match the target rates. In other words, we artificially raise the rates of a player which has relatively lower rates than the target rates (e.g., the players with the hula hoop and treadmill), whereas we decrease the rates of the other users with higher rates than the target rates. Thus, each user u_i has a linear scaling factor β_{u_i} which is used to normalize a player's current speed. As shown in Figure 4, we also propose a simple heuristic which detects whether a player is currently accelerating or decelerating if the rate of change is above some threshold value (line 2). If so, the current state is changed to ACCELERATING or DECELERATING, and the output is scaled accordingly after a fixed amount of time (line 9).

4.3 Balancing Delay Variation

ExerLink uses a client-server model where all players interact with an authoritative game server to play the game, and the server maintains the global state. For a given action that a player takes, the action message is sent to the server. After collecting all the action messages, the server then changes the global state and notifies the resulting state to the players using an update message. In general, the tolerable latency of games with avatars is about 200ms [13], and yet, due to the unique characteristics of game controllers (i.e., changing intensity takes some time), exergames are more lenient to the delay variations. However, large delay variation would result in a poor game experience, particularly when users are playing over cellular networks [36]. To mitigate the problem we employ dead reckoning technique that allows a local client to predict the state of another player using the last known vectors in between update messages from the server [16].

The global state updates at the game server are propagated through all the remote players whose network delay may be different. Thus, the update messages may be delivered at different times. This means that a player who is close to the game server will see the update message earlier and may be able to react faster than the rest of users, which leads to an unfair advantage for the players with lower delays. At the server side, the action messages must be properly ordered such that players' responses are ordered based on their reaction times (i.e., the time duration between update message arrival and action message departure). Several earlier work addressed this issue of fair-ordering of action messages such as Sync-MS [29] and Fair-Ordering [18]. In the Sync-MS service, the game server can process action messages in a fair order based on the following assumptions; i.e., the clocks of all the participants (including the server) are synchronized, and the one-way delay from the server to each player is measured. In contrast, the Fair-Ordering service does not have such requirements and yet provides fair-ordering by simply processing the action message in the order of increasing *reaction time* that is the time between the reception of an update message and the departure of an action message by a player. The server processes all the action messages received during a waiting window and handles the delayed and out-of-order action messages. In ExerLink, we adopt the Fair-Ordering service to balance delay variation in social exergames.

5. EXERCISE-GAME CONTROLLER PROTOTYPE

We discuss our design considerations and technical explorations in redesigning RIA exercise devices as game controllers. There are a number of exercises that belong to the RIA category such as running, biking, hula-hooping, rowing, and jump-roping. We can largely classify these exercises based on the types of exercise equipment (either stationary machines or portable devices). For the purpose of prototyping, we chose treadmill running and stationary cycling for the exercises on machines, and hula-hooping and jump-roping for exercises with handheld equipment.

We modified the existing RIA exercise devices to measure the exercise intensities in real-time. To this end, we implanted sensors and micro-controllers onto an off-the-shelf hula hoop and a jump rope. For the treadmill and stationary cycle, their built-in sensing capabilities are exploited. We carefully augmented existing devices so as not to disrupt the players' natural exercise activities.

The entire prototyping procedure consists of a series of iterations. Importantly, we revised our technical designs of the prototypes until we resolved most of dissatisfaction reports during game plays. The three tests were carried out over eight months. Total 21 paid participants were recruited, and their ages range from 20 to 35. The participants were allowed to freely use all kinds of RIA controllers developed for that test. We interviewed them and collected comments to guide the revision of the controllers which in most cases inspired us with ideas for improvements. Below, we report

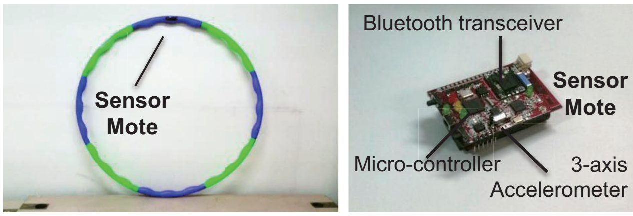


Figure 5: The first hula hoop controller prototype measures rotation speed of the hoop by analyzing a waveform of centrifugal force.

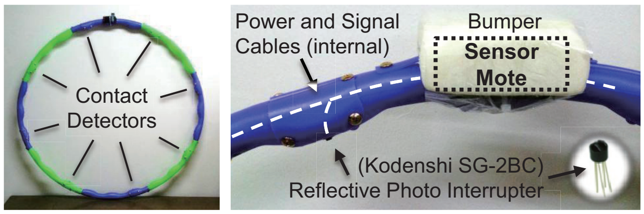


Figure 6: The revised hula hoop, measuring rotation speed eight times faster than the previous one

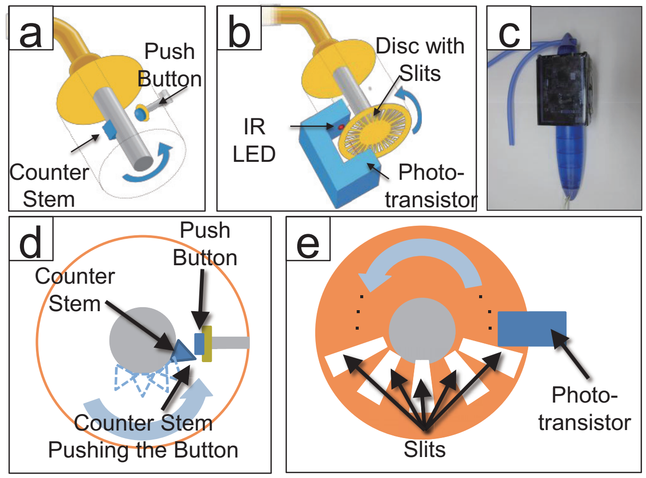


Figure 7: Conceptual diagram of measuring components for (a) the first prototype and (d) the illustration of its functionality. The improved version and its functionality is illustrated in (b) and (e), respectively. The exterior of the improved version is provided in (c)

our design process and key implementation details for each controller.

5.1 Hula Hoop

Our initial attempt was to use minimal sensor hardware and to largely rely on subsequent signal processing. We modified an off-the-shelf hula hoop by integrating a single sensor mote with a built-in 3-axis accelerometer and a Bluetooth transceiver. Figure 5 shows our original hula hoop design. We embedded a sensor mote inside the hula hoop tube, placing the X-axis of the accelerometer facing away from the center of the hoop. Our original strategy with the sensor mote was to measure the centrifugal force exerted when the player revolves the hoop around the waist. Note that the centrifugal force shows periodic characteristics, as the radius of rotation, the distance between the player's body and the sensor mote varies periodically while the hoop rotates. Then we measured the period and evaluated the hoop's rate of rotation. However, our tests showed that the duration of the period was typically too long when we tested the hoop as a game input. Many testers reported that the game value was updated too slowly even when they changed their hula-hooping rates quickly. It makes the game play unresponsive and frustrating.

To address these problems, we revised the design of a hula hoop to detect the contacts between the hoop's inner surface and the player's waist. Then the rate of rotation is calculated from the number of contacts per unit time. This revised design can update changes of the hoop's RPM much more frequently. To this end, we integrated eight reflective photo interrupters (Kodenshi SG-2BC) along the eight equi-spaced points of the inner circumference of the hoop as shown in Figure 6. These interrupters are wired to the sensor mote. This revision allowed us to increase the sampling rate by eight times over the original design, providing sufficient responsiveness to the game experiences.

5.2 Jump Rope

Similar to the initial approach of a hula hoop, we adopted the angular velocity of the rope measured at the grip as the game input parameter. Our original design was to install a counter stem and a button inside of the grip as shown in Figure 7 (a), along with an Atmega128L micro-controller and a Bluetooth transceiver. This design is simple to implement; the counter stem rotates together with the rope, pushing the button once every revolution of the rope as shown in 7 (d). The micro-controller computes the period of a revolution and converts it to angular speed. Lastly, the transceiver reports the value to the local game system.

We identified two major drawbacks of this mechanical counter. First, it was not sufficiently durable; the button-stem tends to loose after a few weeks and eventually failed after a few months in our field trials. Second, and more importantly, updating the rotation frequency once per revolution was not frequent enough in terms of the sampling rate. Its negative impact on the game experience was worse than in the hula hoop case, largely because the jump-ropers were generally able to slow down more abruptly than the hula hoopers. Note that the update interval gets longer as the jump-roping slows down. Many players complained that the game was not responsive enough especially when they intended to slow down abruptly.

To address these drawbacks, we devised an alternative scheme inspired by an opto-mechanical trackball [25]. We installed a small disc with 60 closely spaced radial slits, an LED, and a photo-transistor as shown in Figure 7 (b) and (e). As illustrated in Figure 7 (e), the photo-transistor can detect the presence the IR light if a slit lies upon the location of the transistor (i.e., logical one); otherwise, the IR light will be physically blocked (i.e., logical zero). Based on this method, we can measure the angular speed of the rope 60 times per revolution of the rope, or equivalently, at a sampling rate of 60 times higher than that in the original button-based design. Eliminating a mechanical button also improved the durability; the revised rope survived the entire prototyping phase.

Figure 8: Interactive treadmill (left) and Stationary bicycle (right)

5.3 Stationary Bike

We built two types of bikes that differed in the location where the magnetic rotation sensor is installed: one that measures cadence on the flywheel, which controls the level of resistance, and the another that measures the cadence on the pedal shaft directly. We chose the latter ones, as shown in Figure 8, because the flywheel still rotates even when the player stops pedaling. As we intend to employ the player's current cadence as the game input, measuring flywheel RPM would provide an inaccurate cadence information. In our prototype, we use a mote to collect the data which are wirelessly delivered to the local game client via Bluetooth. The player's cadence is automatically measured and reported periodically in RPM.

5.4 Interactive Treadmill

In order to enhance a treadmill with interactive features required for game inputs, we designed and developed an interactive treadmill that builds upon our earlier work [6] (see Figure 8). In the case of a conventional treadmill, the speed of a treadmill is usually fixed by players or a predefined workout plan. In contrast, the interactive treadmill naturally adjusts its speed to the player's running pace. In detail, the built-in ultrasonic sensors monitor the player-to-console distance, automatically matching the treadmill's speed to the player's pace. Therefore, the interactive treadmill enables players to play games simply by changing their running pace, i.e., when the player increases running speed, she gets closer to the front of the treadmill, and subsequently, the treadmill speeds up; similarly, when she decreases her running speed, the treadmill slows down. Note that unlike other devices, players should be familiarized with the controlling mechanism of an interactive treadmill. Hence, it may take a slightly longer time for players to learn how to control the speed of a treadmill when compared to the cases of other exercise devices. In the following section, we take into account this learning effect in the experiments.

6. EVALUATION OF EXERCISE-GAME CONTROLLERS

We evaluate the performance of the prototype controllers by conducting an experiment concerning a basic and essential pointing activity—most of the core mechanics of the target exergames can be implemented on the basis of this pointing activity. For comparison, we basically measured how rapidly and accurately users can change a game value to a desired level.

6.1 Method

Participants: We recruited 20 participants (10 males and 10 females) via announcements posted in a local university campus. We advertised that the experiments may require sufficient physical abilities in four kinds of exercises as well as stamina. The participants were undergraduate or graduate students in the age range of 18 to 34. The average age was 22.35 (SD: 4.60).

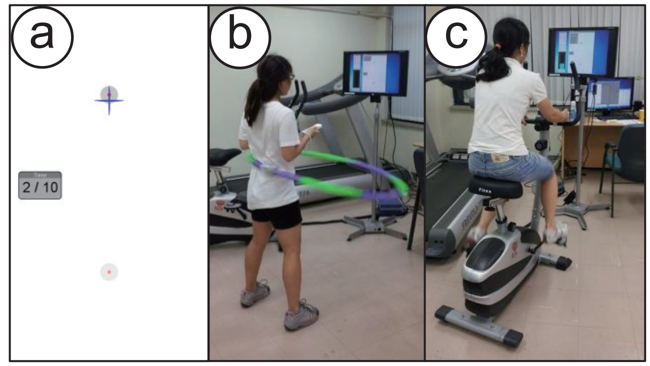


Figure 9: (a) Screenshot of the experiment. (b)(c) Participants performing the experiment using a hula hoop and a stationary cycle

Apparatus: The usability test software was developed in Unity, a casual game development framework. Output was presented on a 24" monitor. Input was via the aforementioned four exercise equipments. A wireless handheld button was given to each participant to click the targets.

Procedure and Design: We randomly assigned participants to one of the four groups (i.e., 5 participants per group). Each participant performed the tests with all four devices. The order of devices in each group was shuffled by following a balanced Latin square experiment design.

To measure the pointing performance, we designed a simplified 1-dimensional version of the multi-directional point-select task as defined in ISO 9241-9 (also known as Fitts' law tests) [22]. As shown in Figure 9 (a), there are two targets at the high intensity position (80% point of the converted game value) and the low intensity position (20%). The distance between the targets and the diameter of the targets are 480 pixels (130 mm) and 48 pixels (13 mm), respectively. The nominal index of difficulty [35] was 3.46 bits.

For each trial, participants moved the cross pointer to the current target using the exercise equipment and then clicked a button of the wireless handheld device to mark the target. After the click, the current target disappears and the next target appears in the opposing position. Participants repeated this task for 10 times (called a block), i.e., five times for acceleration and five times for deceleration. For each equipment, a series of 10 blocks were repeatedly performed. To evaluate the pointing performance, we collected movement times between the clicks and errors on distance between the targets and the clicked positions. From these data, we derived the throughput according to the ISO guidelines [22]. Before the beginning of the experiment, the participants were instructed using a demonstration and given a sequence of warm-up trials. During the warm-up trials, equipment settings were personalized, including adjusting the preferred ranges and controlling the resistance level of the bike.

Because the performance can be influenced by a participant's physical capability and stamina, we periodically reminded the participants' physical condition and asked them to take a rest if they look/feel tired in order to avoid the

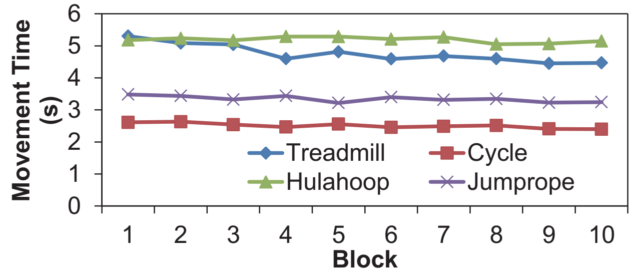


Figure 10: Movement time by equipment and block

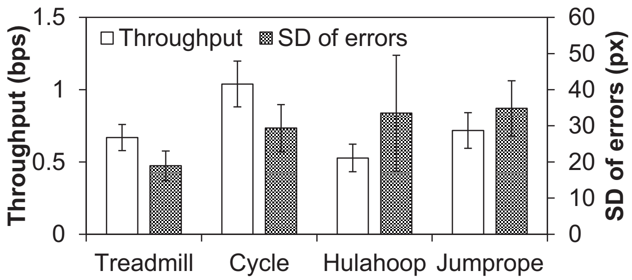


Figure 11: Throughput and SD of errors with 95% confidence intervals

physical conditions that could potentially degrade overall performance. Also, during the intermissions between blocks, the participants were given time for a rest, and beverages were supplied. The total duration of each experiment was around two hours. During the experiment, if participants loose control of the jump rope or the hula hoop, the corresponding trial was discarded and retried. The experiment was a 4×10 within-subjects design. The participants performed a total of 8000 clicks (20 participants $\times$ 10 clicks $\times$ 4 equipments $\times$ 10 blocks).

6.2 Results

6.2.1 Movement Time and the Learning Effect

As mentioned above, the interactive treadmill is equipped with a novel speed controlling mechanism. Given that all the participants had no previous experience with such an interactive treadmill, participants had to get familiar with the tests. Therefore we tried to check whether a learning effect exists. Figure 10 shows the effects of learning (i.e., block) and exercise equipment on movement time. The main effect was significant for equipment ($F_{4,760} = 407.8$, $p < 0.001$). The main effect for block and the equipment by block interaction were not significant.

However, still we can find that there seems to be the learning effect in the case of the treadmill, as shown in Figure 10. We further tested the learning effects for each equipment, and found significant differences on movement time between blocks in the case of the treadmill only ($F_{9,190} = 2.66$, $p < 0.01$). We analyzed the Helmert contrasts by following the work [35], and it showed that the block effect was not significant after block three. Therefore, in the subsequent analysis we used the mean of blocks ranging from four to ten.

The average movement time was $4.60s$ for the treadmill, $2.47s$ for the cycle, $5.19s$ for the hula hoop, and $3.31s$ for the jump rope. Paired t-tests revealed significant differences in movement time across all equipment combinations except between treadmill and hula hoop. The stationary bike was the fastest equipment, and the treadmill and the hula hoop were among the slowest.

6.2.2 Throughput and SD of errors

The throughput was 0.67 for the treadmill, 1.04 for the bike, 0.53 for the hula hoop, and 0.72 for the jump rope. The main effect on the type of equipment was clearly significant ($F_{3,76} = 14.22$, $p < 0.001$). Paired t-tests revealed significant differences in throughput across all equipment combinations except between treadmill and jump rope. However, the characteristics between these two types of equipment are somewhat different; the treadmill shows slower movement time and a lower standard deviation (SD) of errors, whereas the jump rope shows faster movement time and a higher SD of errors.

6.2.3 Movement Direction Effects

We found that there are differences in the measures for the two movement directions: up and down. We tested differences between directions as well as between exercise types using a two-way ANOVA test on the throughput, the movement time and the SD of errors. In overall, a main effect of direction was found, indicating that the throughput of *down* was greater than that of *up* ($F_{1,152} = 19.6$, $p < 0.001$) at the lower SD of errors ($F_{1,152} = 14.79$, $p < 0.001$) and the shorter movement time ($F_{1,152} = 24.87$, $p < 0.001$). This result indicates that increasing exercise speeds is harder than decreasing speeds. For example, in the case of the hula hoop, players should rotate their waist faster to increase the hooping speed, whereas they can easily decrease the speed by simply relaxing. Our balancing scheme on the device heterogeneity copes with these performance differences in movement directions by treating acceleration and deceleration rates separately, as mentioned earlier in Section 4.2.

6.2.4 Gender Effects

We observe the performance difference between male and female participants. We tested whether there exist a gender effect as well as an interaction effect between gender and exercise type using a two-way ANOVA test on the throughput, the movement time and the SD of errors. We found a main effect of gender, which indicates that the female participants achieved significantly greater throughput ($F_{1,72} = 66.56$, $p < 0.001$) at the fairly low errors ($F_{1,72} = 26.71$, $p < 0.001$) and the faster movement time ($F_{1,72} = 6.39$, $p < 0.05$).

Interestingly, there was an interaction between gender and exercise type only on the movement time ($F_{3,72} = 2.22$, $p < 0.1$). Simple effects tests showed that the movement time of the female participants did not show significant differences between exercise types ($F_{3,36} = 2.07$, $p > 0.1$), whereas the male participants did ($F_{3,36} = 3.00$, $p < 0.05$). Actually, we observed that the male participants tend to have larger preferred ranges than those of the female participants. We conjecture that these differences on preferred ranges affect the performance of controlling the game values.

One more interesting observation is that the errors of the female participants on hula hoops are quite lower than those of the male participants. From the open-ended exit interview, we found that about half of the male participants reported that it was unusual to change the speed of hulahooping, whereas only one female participant reported the same. Recalling gender differences on physical abilities such

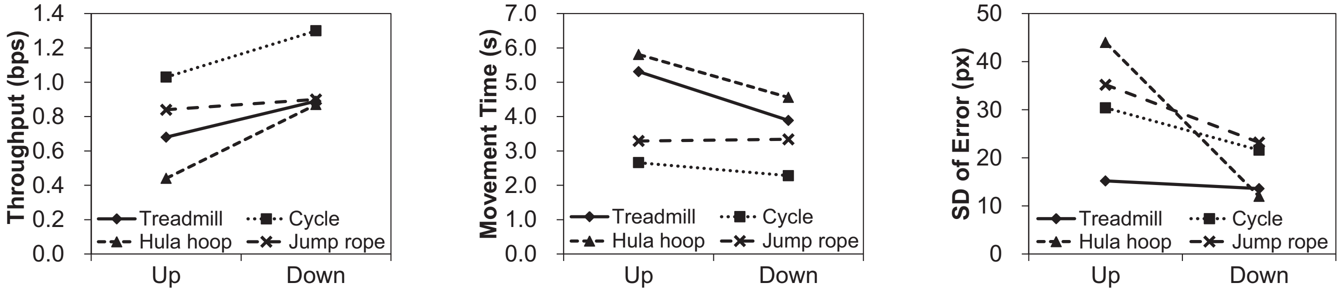


Figure 12: Interaction effects of movement direction and exercise type

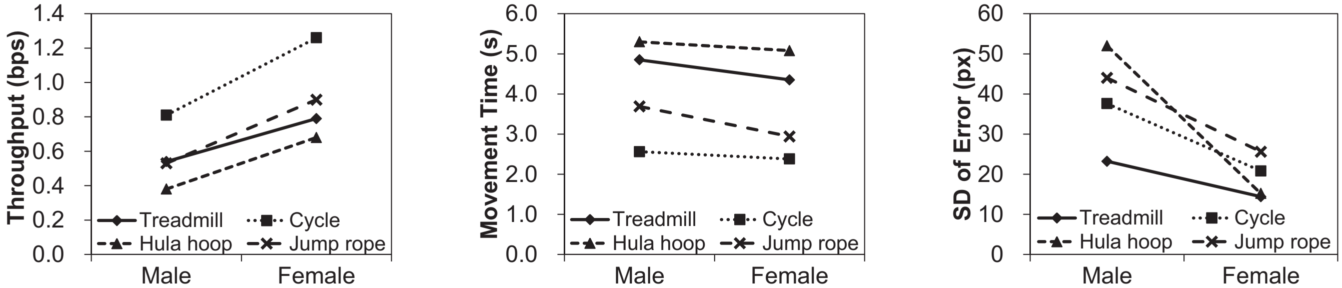


Figure 13: Interaction effects of gender and exercise type

as strength and flexibility [9], it is required to give careful attention on the gender differences. In some cases, it is possible to actively utilize these differences, as the traditional role playing games usually do in their character design, to motivate players to build their own strategy to cope with the differences.

7. CASE STUDIES WITH SWAN BOAT

We conducted two case studies to observe (1) whether our balancing scheme results in a fair game play of Swan Boat (Section 7.1), and (2) patterns of social interactions among remote game players (Section 7.2). In both case studies, we use Swan Boat with the four types of RIA exercise equipment as game controllers. For the remote exercise experiments, we use KT WiBro portable wireless routers (Egg KWI-B2200) for the players with a hula hoop and jump rope.[3]

7.1 Case Study 1: Balancing and Fairness

7.1.1 Method

For this study, we recruited 20 paid participants from the age group 20 to 29, via announcements posted in a local university campus. We assured that none of the participants joined the earlier experiments. The selected participants went through a training session to get familiarized themselves with the exercise equipment. The participants were given an hour for training. The training session was separately held a day before the experiments, to ensure enough time to recover from fatigue. The 20 participants were randomly divided into five groups with the same size, and each group was divided into two teams (each team with two members). The two teams of the same group competed with one another in the boat race.

Experiment setting and procedure: We asked the participants to compete in a race; i.e., the goal is to reach the finish line faster than the opponent team to win the race. The game was played over the 'rally map,' designed for a short fun race and close collaboration between the teammates. It has a winding path, and the path includes many obstacles. In addition, two types of items are randomly distributed along the path; they are boosters which increase the boat speed for 3 seconds, and traps which decreases the boat speed for 3 seconds. The length of a race was set to be about 2 minutes. To see the collaboration and competition effect altogether, we had one team use a heterogeneous pair of the exercise devices and had the other team use a homogeneous pair of exercise devices in order to compare the game performance. We also ensured that all exercise types were used in the games. Thus, we had the competing two teams play a total of four games.

We collected data from questionnaires, interviews, and game statistics including win/loss records, finishing times, etc. We also examined the participants' conversations during the experiment. The participants were asked to answer a short questionnaire at the end of a session. The questionnaire included a set of statements (e.g., the game is fun), and the participants were asked to rate each statement using a five-point Likert scale (5=highly agree). The exit interview was conducted to better understand questionnaire responses.

7.1.2 Results

Table 1 shows the game records of the 20 matches. The results show that players with different RIA controllers can collaborate and compete well while playing the game. A team composed of heterogeneous RIA controllers shows comparable game performance to a team composed of homogeneous RIA controllers. The game statistics clearly show that the game is playable with heterogeneous RIA controllers. The game performance was also comparable between the homogeneous exercise pair and the heterogeneous exercise pair.

The responses from the participants did not explicitly demonstrate the fairness issues between parings of exercise

[3]Egg KWI-B220 supports nation-wide WiBro connectivity (whose performance is comparable with a 4G LTE cellular network).

Table 1: Game records of the 20 matches

	Homogeneous team	Heterogeneous team
Playing time (sec)	86.30	86.35
# of acquired items	3.35	3.40
# of obstacle collisions	3.30	3.30
# of wins	11	9

types. Among the participants, some answered that the exercise type influenced the outcome whereas some did not. 45% agreed to the statement 'it is possible to win the game regardless of exercise types,' and 30% (strongly) disagreed. As for the statement 'other factors, such as exercise or game capability, influence the outcome of the race more than the exercise type,' 55% agreed whereas 40% disagreed.

However, contrary to the reports, we speculate that the exercise type is not a major factor of affecting the outcome. Considering those who disagreed to these statements, we tried to identify whether certain exercise types are commonly pointed out to be advantageous or disadvantageous. Interestingly, we found that the selection of such exercise types varied depending on the participants. It seemed their perception of unfairness is largely induced by the fact that their personal skills in the exercise types vary as well. For example, some participants said the jump rope appeared to be the most advantageous exercise type because it was easy to control the speed. In contrast, there was another participant gave an opposite explanation that it was hard to control the jump roping speed. Conflicting descriptions were made for the hula hoop and stationary cycle as well.

In addition, a majority agreed that teammates' exercise type is not a major factor for the outcome. 65% agreed to the statement 'other factors, such as teammate's exercise capability, have a greater influence than the partners' exercise type,' whereas 20% disagreed. The participants who agreed brought up many factors: for example, the teammate's skill in the exercise type, collaboration ability, and understanding of their exercise type.

7.2 Case Study 2: Social Interactions

7.2.1 Method

For this case study, a total of 16 paid students were recruited on campus from the age group of 18 to 33. Participants were carefully selected such that there is no participant overlapping with those in the previous case study. In our advertisements, we encouraged the participants to join the study with people whom they were familiar or friends with, because the objective of this case study is to observe social interactions among participants. We had four groups, and each group was divided into two teams of two members to allow competition. The participants went through a training session for an hour in order to familiarized themselves with the exercise equipment, and the actual experiment was conducted the day after the training session.

Experiment setting and procedure: The game setup was similar to that of Section 7.1. This case study involves two sets of experiments representing two different configuration in terms of players' location (i.e., co-located vs. remote play). In the co-located configuration, four exercise devices were placed at the same place, where participants can freely speak to each other. In the remote configuration, each exercise device was placed at an isolated place in the same building such that participants can only communicate via VoIP with Bluetooth headsets. In each set of experiments, participants played a total of four games (i.e., overall eight games were played). Each group performed two set of experiments in two distinct days, and the sequence of the experiments are randomized to mitigate the learning effect. We performed content analysis of participants' conversations during the game play, inspired by previous work on social interactions in online game play [17], and exit interview results to investigate the patterns of social interactions under different experiment configurations.

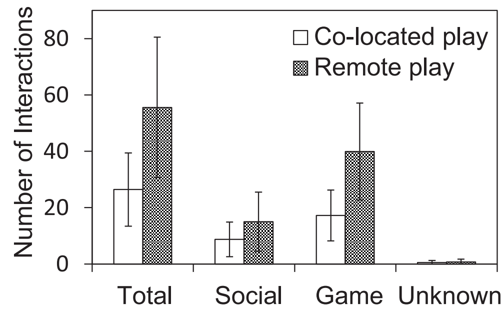


Figure 14: Number of comments between two configurations with 95% confidence intervals. *Total* represents average number of total comments conducted. *Social* and *Game* represent the average number of social and game-instructing comments, respectively. Note that *Undefined* indicates undefined comments that we could not interpret due to background noise.

7.2.2 Results

Our findings show that ExerLink can effectively facilitate social interactions in a remote environment similar to that in a co-located environment. Participants commented on their experiences with our remote social exergame compared to the co-located exergame as follows: *"I didn't feel any inconvenience in communication among people"* [P8], *"When played remotely, my teammate and I could control the boat as if we were in a same room. I could even hear what other teams were saying and use it for our game strategy"* [P4]. In summary, 14 out of 16 participants commented that they did not feel uncomfortable when communicating each other in a remote environment. The results of content analysis on the participants' conversations during the experiments, shown in Figure 14, also support these comments. It even shows that our system increases the average number of conversational exchanges in a remote environment, i.e, the difference on the total number of comments between two configuration is statistically significant ($t(21) = -3.98$, $p < 0.001$). Note that these numbers only include those comments that bring something meaningful during the game. For example, in Figure 14, *Game* represents the average number of comments affecting the game performances controlling the speed or direction of the swan boat (e.g., "go left," "slow down," etc). *Social* includes emotional expression, encouragements or other social conversation that does not affect the game.

It was also interesting to observe that participants tend to focus more on the game in a remote environment: *"When* *we played remotely, I could concentrate more on the game. I actually felt like I was playing Mario Cart"* [P1], *"When we were playing the game in the same room, I felt that I was disturbed when other participants created noise during the game. In contrast, I could fully concentrate on the game at a separate room"* [P11]. Figure 14 shows that the number of the game-instructing comments among the total number of comments increased when participants were playing the game remotely. The difference on the number of the game-instructing comments between two configuration is statistically significant ($t(21) = -4.49$, $p < 0.001$). It supports the above comments that subjects participated in the game more actively.

7.2.3 Potential of ExerLink as a social medium

We found that our system has potential to be a socializing medium. After each experiments, we conducted an exit survey, and an open-ended interview to understand the individual's willingness to use our system and its reason. Most of the participants appreciated the system as an excellent conduit for social experiences while 'playing together,' even in a remote play situation. 14 out of 16 participants (strongly) agreed to the statement 'I am willing to use this system to socialize with acquaintances and friends.' One participant stated: *"I think I can use this system to socialize with others, have fun, and exercise at the same time"* [P5].

Also, the participants liked the socializing feature of the system; they strongly agreed that the game play improved forming bonds between players. One participant stated: *"Before the game play, I and my teammate were not so familiar with each other. However, after playing just two games, I realized that we were chatting together as if we were close friends"* [P8].

In addition, we found that game play with strangers is acceptable. 8 out of 16 participants agreed to the statement 'I will virtually meet and play the game with strangers online,' whereas 3 disagreed. One participant stated: *"I think that it will be not so different to play StarCraft or League of Legends with strangers. If none of my friends are available to play together, I will find my teammates online"* [P13].

8. DISCUSSION

The focus of this study has been on inter-controller differences rather than inter-player differences. To that end, we conducted our study with a tester population of males and females mostly in their 20s. However, we note that there will be differences across age groups. We need to respect these differences and carefully study them to further develop games for broader populations.

Our evaluation results on controller performance are mostly obtained through short-term studies, leaving further studies on human factors to be conducted in a longitudinal study in the near future. We expect that it would be an interesting topic to study the effects of the controller performances as the players get accustomed to using the RIA controllers.

We have suggested guidelines on balanced game design and reported our experiences from case studies to evaluate the effectiveness of the balanced game design. We expect that a certain pattern would be derivable after multiple balancing cases have been accumulated.

This work has studied the effects of our custom-designed exercise equipment in the viewpoint of controlling exergames, yet leaving the effects of actual exercise amount unexplored. While the players enjoy the game as we suggested, it is an important issue to study the amount of exercise involved and the effectiveness of that exercise. Over-exertion, a potential problem which might occur due to the game, is also a concern, requiring careful observation in terms of exercise intensity and duration.

We did not thoroughly investigate the impact of network delay in this work since our focus has been demonstrating the feasibility of multi-exercise social games. During our field trials, we also tried to play Swan Boat over a 3G celluar networks and fortunately did not find any noticeable disruptions thanks to the proposed mechanisms in ExerLink. We are currently investigating the user experience under different network delay/jitter conditions using Dummynet [1].

9. RELATED WORK

As sensor and device technology advances, creating new kinds of exergames has been an active area of research in recent years. Yet existing exergames mostly focused on a single exercise modality and did not consider combining heterogeneous exercises into the same game. Exercise equipment has been revised or newly developed as an exergame such as an arm ergometer [19], an interactive treadmill [6], a spirometer [27], a tangible ball [23], and playful gadgets [11, 12, 30]. Exergame Fitness Co. provides several types of exergame controllers including game cycles, interactive floor and wall systems [3]. Several exergames [15, 40, 43, 45] used heart rate signals for a multi-player game. Mueller et al. recently developed exergames called "sports over distance" that directly use players' physical actions for a remote sport play (e.g., Jogging Over a Distance, Remote Impact, Table Tennis for Three) [37, 39, 40]. Readers can find more information about recent advances in exergames and their design principles and guidelines in the following articles [10, 38, 44]. Note that cellular phones can be also used as game controllers to play a remote game. AirPlay gamifed live TV sports games and shows such that the TV audience can participate in the game using their cell phones while watching TVs [31]; e.g., in "Call the Play Football," people predict how upcoming plays will unfold and those participants who correctly guessed are rewarded. Beyond a means of communications, we expect that recent smartphones with various internal sensors will create new opportunities for developing exergame controllers (e.g., monitoring physical activity levels with accelerometers).

So far little work has been done on assessing the performance or usability of exergame controllers on actual game play. In user interface literature [34, 33, 35], a pointing device's performance (e.g., mouse) is typically measured using the metric called throughput [22]. In addition, some works assessed the performance of game controllers in terms of pointing accuracy and rapidness [26, 41]. In the viewpoint of games, Natapov et al. compared the performance of computer-games when different game controllers are used, namely an Xbox gamepad and a standard PC mouse [42]. The main departure from existing work is that we consider exergame controllers and aim to address heterogeneity of exergame controllers in a multi-player social exergame.

A number of techniques have been proposed for balancing game play between players with disparate abilities, as summarized in the work by Stach et al. [45]. Traditional sports and games (e.g., golf, bowling and chess) used techniques such as handicapping, ladders, and asymmetric roles. These methods are also widely used in computer games in the form of prior simulations, player monitoring [8], and autonomous advantages [20]. Balancing enables inter-generational game play in which players from different generational groups can interact with each other in the same game [46, 23, 24, 44, 47]. For exergames, several works attempted to balance the game play among players with different physical abilities, by sharing heart rate information [15, 40, 43, 45].

There exist several cases that employ different types of game controllers. Rock Band and Guitar Hero successfully incorporate several types of musical-instrument-like controllers to create a metaphor of playing a rock concert. Time Crisis 2 permits the use of the game pad in PlayStation 2 as well as a custom-designed gun-type controller. Age Invaders [24] incorporates heterogeneous types of game controllers, i.e., the floor platform and conventional PC interfaces. However, these games do not address the balancing issues when heterogeneous controllers are used for collaboration and competition.

To our knowledge, there are only a few cases that incorporate multiple types of game controllers in a balanced manner. One impressive effort—in terms of emphasizing the importance of balancing between game controllers in the game development process—is Shadowrun, a multiplayer tactical first-person shooter that provides two different controlling methods, i.e., an Xbox gamepad and a mouse with a keyboard. The developers of this game balanced the disparities by providing game-side advantages or penalties for each controller [2]. In fact, this work gave us one important and practical lesson when creating and evaluating game controllers: *'If the player is blaming the controls for their failures, then we have done something wrong.'*

Exercise heterogeneity in exergames can be addressed by using the exercise intensity information, which can be predicted via the player's physiological status or can be directly measured via modified equipment. Notably, the heart rate is a good physiology metric to use, as it is typically proportional to the exercise intensities regardless of an exercise type [15, 32, 40, 43, 45]. However, a game controller harnessing such a mediated metric is limited in its responsiveness, compared to the one that directly measures the intensity level from exercise equipment. In practice, it takes tens of seconds for a change in the player's exercise intensity to be reflected in her heart rate [32, 45]. Accordingly, heart rate-based controllers cannot effectively deal with fast-paced games in which the players have to respond to changing game conditions within a matter of seconds. In our work, we revamped existing exercise devices to directly measure the intensity level and addressed the heterogeneity problem with a personalized inter-device balancing scheme.

Our framework allows the game designers and developers to easily employ multiple types of controllers at their discretion, thereby delivering more fun—players can choose their favorite equipment through which collaboration and competition can happen in a fair manner. We envision this kind of game development will soon be established in the near future.

10. CONCLUSION

We proposed ExerLink to explore the possibility of using heterogeneous exercise devices as game controllers and to realize pervasive social exergames that transforms isolated disparate exercise activities into a fun collaborative activity. When converting exercise intensity to game input, ExerLink aims to provide fair game play experiences by carefully considering the unique aspects of social exergames such as heterogeneity of exercise devices and personal differences of capabilities and preferences. We designed and implemented four exergame controllers by significantly augmenting existing exercise devices and performed preliminary human subject studies to evaluate the performance of exergame controllers and the user experience of an exergame. Our study results show that players with different exercises can effectively collaborate and compete well while playing the same game. In remote exergames, we found that missing visual cues of other players did not make any significant impact on the game play experiences, and yet, players were more engaged in both conversation and exercise as opposed to co-located exergames.

11. ACKNOWLEDGMENTS

We thank all of the subjects who participated in this study. Special thanks to our shepherd, Dr. Mirjana Spasojevic, and all the anonymous reviewers for their great reviews. This work was supported by the National Research Foundation of Korea grant (No. 2011-0018120) funded by the Korean Government (MEST), and the SW Computing R&D Program of KEIT (2011-10041313, UX-oriented Mobile SW Platform) funded by the Ministry of Knowledge Economy of Korea.

12. REFERENCES

[1] Dummynet, http://info.iet.unipi.it/∼luigi/dummynet, 2009.

[2] Controller Balancing, http://replay.web.archive.org/20071011062350/http://shadowrun.com/backstage/controller_balancing.htm, 2012.

[3] Exergame Fitness, http://www.exergamefitness.com, 2012.

[4] Nike + iPod, http://www.apple.com/ipod/nike, 2012.

[5] Wii Sports, http://wiisports.nintendo.com, 2012.

[6] M. Ahn, S. Kwon, B. Park, K. Cho, S. Choe, I. Hwang, H. Jang, J. Park, Y. Rhee, and J. Song. Running or gaming. In *Proceedings of the International Conference on Advances in Computer Enterntainment Technology*, pages 345–348. ACM, 2009.

[7] B. Ainsworth, W. Haskell, M. Whitt, M. Irwin, A. Swartz, S. Strath, W. O'BRIEN, D. Bassett, K. Schmitz, P. Emplaincourt, et al. Compendium of physical activities: an update of activity codes and met intensities. *Medicine & Science in Sports & Exercise*, 32(9):S498, 2000.

[8] T. Alexander. *Massively Multiplayer Game Development.* Charles River Media, 2003.

[9] M. Alter. *Science of flexibility.* Human Kinetics Publishers, 2004.

[10] T. Campbell, B. Ngo, and J. Fogarty. Game design principles in everyday fitness applications. In *Proceedings of the ACM conference on Computer supported cooperative work*, pages 249–252. ACM, 2008.

[11] Y. Chang, J. Lo, C. Huang, N. Hsu, H. Chu, H. Wang, P. Chi, and Y. Hsieh. Playful toothbrush: ubicomp technology for teaching tooth brushing to kindergarten children. In *Proceedings of the 26th annual sigchi conference on human factors in computing systems*, pages 363–372. ACM, 2008.

[12] M. Chiu, S. Chang, Y. Chang, H. Chu, C. Chen, F. Hsiao, and J. Ko. Playful bottle: a mobile social persuasion system to motivate healthy water intake. In *Proceedings of the 11th international conference on Ubiquitous computing*, pages 185–194. ACM, 2009.

[13] M. Claypool and K. Claypool. Latency and player actions in online games. *Communications of the ACM*, 49(11):40–45, 2006.

[14] S. Consolvo, K. Everitt, I. Smith, and J. Landay. Design requirements for technologies that encourage physical activity. In *Proceedings of the SIGCHI conference on Human Factors in computing systems*, pages 457–466. ACM, 2006.

[15] R. de Oliveira and N. Oliver. Triplebeat: enhancing exercise performance with persuasion. In *Proceedings of the 10th international conference on Human computer interaction with mobile devices and services*, pages 255–264. ACM, 2008.

[16] C. Diot and L. Gautier. A distributed architecture for multiplayer interactive applications on the internet. *Network, IEEE*, 13(4):6–15, 1999.

[17] N. Ducheneaut and R. Moore. The social side of gaming: a study of interaction patterns in a massively multiplayer online game. In *Proceedings of the 2004 ACM conference on Computer supported cooperative work*, pages 360–369. ACM, 2004.

[18] K. Guo, S. Mukherjee, S. Rangarajan, and S. Paul. A fair message exchange framework for distributed multi-player games. In *Proceedings of the 2nd workshop on Network and system support for games*, pages 29–41. ACM, 2003.

[19] S. Guo, G. Grindle, E. Authier, R. Cooper, S. Fitzgerald, A. Kelleher, and R. Cooper. Development and qualitative assessment of the gamecycle exercise system. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 14(1):83–90, 2006.

[20] J. Habgood and M. Overmars. *The Game Maker's Apprentice: Game Development for Beginnerst*. Apress, 2006.

[21] W. Haskell, I. Lee, R. Pate, K. Powell, S. Blair, B. Franklin, C. Macera, G. Heath, P. Thompson, and A. Bauman. Physical activity and public health: updated recommendation for adults from the american college of sports medicine and the american heart association. *Medicine & Science in Sports & Exercise*, 39(8):1423, 2007.

[22] ISO 9241-1. *Ergonomic requirements for office work with visual display terminals (VDTs) - Part 9: Requirements for non-keyboard input devices*. International Organization for Standardization, 2000.

[23] D. Kern, M. Stringer, G. Fitzpatrick, and A. Schmidt. Curball–a prototype tangible game for inter-generational play. In *Workshops on Enabling Technologies: Infrastructure for Collaborative Enterprises*, pages 412–418. IEEE, 2006.

[24] E. Khoo, T. Merritt, and A. Cheok. Designing physical and social intergenerational family entertainment. *Interacting with computers*, 21(1-2):76–87, 2009.

[25] S. Kim. Trackball device. *US Patent*, 4404865, 1983.

[26] C. Klochek and I. MacKenzie. Performance measures of game controllers in a three-dimensional environment. In *Proceedings of Graphics Interface 2006*, pages 73–79. Canadian Information Processing Society, 2006.

[27] B. Lange, S. Flynn, A. Rizzo, M. Bolas, M. Silverman, and A. Huerta. Breath: a game to motivate the compliance of postoperative breathing exercises. In *International Conference on Virtual Rehabilitation, 2009*, pages 94–97. IEEE, 2009.

[28] J. Lin, L. Mamykina, S. Lindtner, G. Delajoux, and H. Strub. Fish'n'steps: Encouraging physical activity with an interactive computer game. *UbiComp 2006: Ubiquitous Computing*, pages 261–278, 2006.

[29] Y. Lin, K. Guo, and S. Paul. Sync-ms: Synchronized messaging service for real-time multi-player distributed games. In *10th IEEE International Conference on Network Protocols*, pages 155–164. IEEE, 2002.

[30] J. Lo, T. Lin, H. Chu, H. Chou, J. Chen, J. Hsu, and P. Huang. Playful tray: adopting ubicomp and persuasive techniques into play-based occupational therapy for reducing poor eating behavior in young children. *UbiComp 2007: Ubiquitous Computing*, pages 38–55, 2007.

[31] D. B. Lockton. Live television show utilizing real-time input from a viewing audience. *US Patent*, 0028272, 2007.

[32] B. Maciel, L. Gallo, J. Marin Neto, and L. Martins. Autonomic nervous control of the heart rate during isometric exercise in normal man. *Pflügers Archiv European Journal of Physiology*, 408(2):173–177, 1987.

[33] I. MacKenzie. Fitts' law as a research and design tool in human-computer interaction. *Human-computer interaction*, 7(1):91–139, 1992.

[34] I. MacKenzie and P. Isokoski. Fitts' throughput and the speed-accuracy tradeoff. In *Proceedings of the 26th annual SIGCHI conference on Human factors in computing systems*, pages 1633–1636. ACM, 2008.

[35] I. MacKenzie, T. Kauppinen, and M. Silfverberg. Accuracy measures for evaluating computer pointing devices. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 9–16. ACM, 2001.

[36] J. Manweiler, S. Agarwal, M. Zhang, R. Roy Choudhury, and P. Bahl. Switchboard: a matchmaking system for multiplayer mobile games. In *Proceedings of the 9th international conference on Mobile systems, applications, and services*, pages 71–84. ACM, 2011.

[37] F. Mueller and S. Agamanolis. Sports over a distance. *Computers in Entertainment (CIE)*, 3(3):4–4, 2005.

[38] F. Mueller, M. Gibbs, and F. Vetere. Taxonomy of exertion games. In *Proceedings of the 20th Australasian Conference on Computer-Human Interaction: Designing for Habitus and Habitat*, pages 263–266. ACM, 2008.

[39] F. Mueller, M. Gibbs, and F. Vetere. Design influence on social play in distributed exertion games. In *Proceedings of the 27th international conference on Human factors in computing systems*, pages 1539–1548. ACM, 2009.

[40] F. Mueller, F. Vetere, M. Gibbs, D. Edge, S. Agamanolis, and J. Sheridan. Jogging over a distance between europe and australia. In *Proceedings of the 23nd annual ACM symposium on User interface software and technology*, pages 189–198. ACM, 2010.

[41] D. Natapov, S. Castellucci, and I. MacKenzie. Iso 9241-9 evaluation of video game controllers. In *Proceedings of Graphics Interface 2009*, pages 223–230. Canadian Information Processing Society, 2009.

[42] D. Natapov and I. MacKenzie. Gameplay evaluation of the trackball controller. In *Proceedings of the Conference on the Future of Game Design and Technology*, pages 167–174. ACM, 2010.

[43] V. Nenonen, A. Lindblad, V. Häkkinen, T. Laitinen, M. Jouhtio, and P. Hämäläinen. Using heart rate to control an interactive game. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 853–856. ACM, 2007.

[44] J. Sinclair, P. Hingston, and M. Masek. Considerations for the design of exergames. In *Proceedings of the 5th international conference on Computer graphics and interactive techniques in Australia and Southeast Asia*, pages 289–295. ACM, 2007.

[45] T. Stach, T. Graham, J. Yim, and R. Rhodes. Heart rate control of exercise video games. In *Proceedings of Graphics interface 2009*, pages 125–132. Canadian Information Processing Society, 2009.

[46] V. Vanden Abeele and B. Schutter. Designing intergenerational play via enactive interaction, competition and acceleration. *Personal and Ubiquitous Computing*, 14(5):425–433, 2010.

[47] F. Vetere, H. Davis, M. Gibbs, P. Francis, and S. Howard. A magic box for understanding intergenerational play. In *CHI'06 extended abstracts on Human factors in computing systems*, pages 1475–1480. ACM, 2006.