Machine-Mediated Teaming: Mixture of Human and Machine in Physical Gaming Experience

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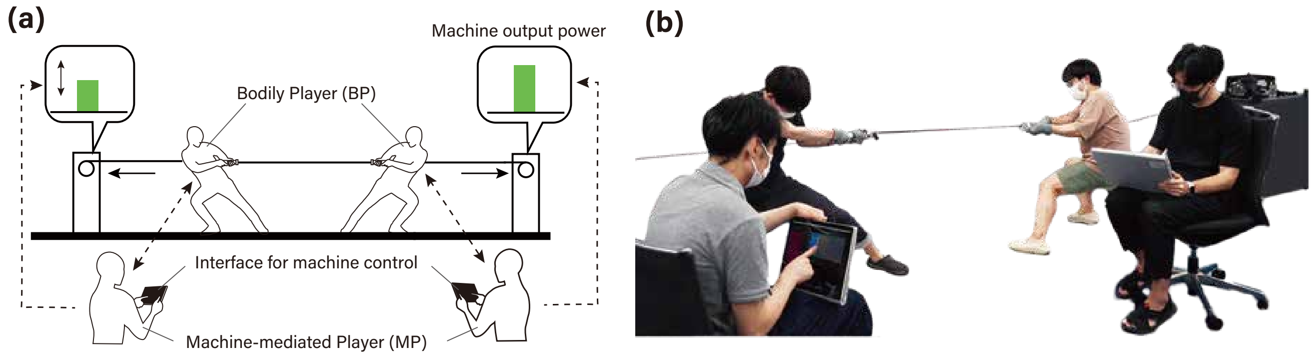

Figure 1: (a) Framework of a system developed for a case study of machine-mediated teaming based on tug-of-war. (b) A scene of an actual game being played using our developed system.

ABSTRACT

Technological advancement has opened up opportunities for new sports and physical activities. We introduce a concept called *machine-mediated teaming*, in which a human and a surrogate machine form a team to participate in physical sports games. To understand the experience of machine-mediated teaming and the guidelines for designing the system to achieve the concept, we built a case study system based on tug-of-war. Our system is a sports game played by two against two. One team consists of a player who actually pulls the rope and another player who participates in the physical game by controlling the machine's actuators. We conducted user studies using this system to investigate the sport experience in this form and to reveal insights to inform future research on machine-mediated teaming. Based on the data obtained from the user studies, we clarified three perspectives, machine stamina, action space, and explicit feedback, that should be considered when designing future machine-mediated teaming systems. The research presented in this paper offers a first step towards exploring how humans and machines can coexist in highly dynamic physical interactions.

CCS CONCEPTS

• **Computer systems organization** → **Sensors and actuators**; • **Human-centered computing** → *Interaction design*; Interaction devices.

KEYWORDS

human-machine collaboration, physical interaction, sports design, augmentation

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1 INTRODUCTION

Sports have evolved and diversified under the influence of technology. The invention of the gasoline engine led to the birth of motor sports, and computing technologies formed e-sports. Recent technologies have also provided opportunities for the creation of new sports and physical experiences. The development of sensors and interactive technologies have fueled research on design and analysis of interactive games using bodily movement [23, 25, 29] and the spreading of commercial products, e.g., Nintendo Ring Fit Adventure [36]. Human augmentation and bodily integrated technologies have motivated researchers to design new sports and interactive games [14, 28].

These emerging fields have the potential to offer users new experiences and enjoyment in various forms. However, in games where the user's bodily movement has a dominant influence, such as games that require highly dynamic and interdependent exertion [30], it is difficult for people with different fitness levels to team up together. Here, interdependence is referred to as an experience in which each player's actions affect others in ways that interfere with or assist them, such as in ball games or combat sports. It is still challenging for users with large differences in size and basic motor skills to directly and physically share the experience of interdependent exertion in games involving multiple people.

In this study, we focus on team sports and explore how interactive technologies can reconstruct team sports. We propose a form of mixed human-machine sport, named "machine-mediated teaming" (hereafter MMT). In MMT, there are two types of players: one is a player that we call the *Bodily Player* (hereafter BP), who uses their own body to perform physical movements in a game, and the other is called the *Machine-mediated Player* (hereafter MP), who participates in the game by controlling specialized machines from outside and performing movements (Fig. 1 (a) shows a BP and MP in a specific MMT system). BPs and machines coexist on a field and physically interact with each other. By mixing these two different types of players in a team, each role and ability will be redefined. This means that MPs require intelligence to properly use the machines' motor abilities instead of their own bodies. Thus, MMT provides an inclusive sport that allows people with handicaps to participate in a game with interdependent exertion.

A key factor in creating a team sports experience in MMT would be how to offer equal influence to BPs and MPs in the game. This is because if the influence of the BP and the MP on the game is not balanced, there will be no room for cooperation and the development of team relationships. However, it is not obvious how equal dominance can be achieved for two completely different entities, human and machine. To address this issue, this study aims to reveal insights into understanding and designing MMT experiences.

As a case study, we developed a specific system for an example of MMT, as shown in Fig. 1. We focus on tug-of-war and design the system by placing some team members as MPs. This is because that tug-of-war as a base sport for its simplicity and strategic aspects, and it requires interdependent exertion. While the players' action is only to control the pulling force, this sport has a lot of strategic aspects, such as how to apply force, how to judge the condition of the opponent, and how to cooperate with the other players in the team [50].

In our system, the BP uses its own body to pull the rope, while the MP participates in the game with the machine behind the BP. The MP can pull the rope externally with human-scale force by leveraging the machine and the control interface. With our motivation of investigating the MMT sports experience and revealing insights for designing MMT, we conducted user studies. We first conducted a pilot user study to identify system parameters to be improved to enable our system to offer a team sport experience. Then, we adjusted the parameters identified in the pilot user study and conducted an exploratory user study to validate our proposed concept. Based on the findings revealed in this process, we discuss perspectives and implications for designing future MMT systems.

This paper is organized as follows: 1) we propose a concept called machine-mediated teaming, in which human and machine motions cooperate to play physical team sports, 2) we develop a system based on tug-of-war, a one-dimensional physical team sport, 3) we conduct user studies to validate our concept and reveal several insights for designing MMT and relationships between humans and machines.

2 RELATED WORK

2.1 Machines in Collaborative Work

Machine mediation for collaborative work has been investigated in various research fields. Teleoperated robots enable the user to participate in group work or interact with other people in many situations, including attending conferences [32, 33, 40], working in offices [17, 51], spending time with a long-distance partner [52], and solving puzzle games [45]. These activities can also enhance the quality of life for people with disabilities by improving their social connections [24]. While the scope of these works is to investigate users conversations and communications, collaboration in physical tasks or with physical interaction using teleoperated robots, such as surgery [39, 46], has also been explored. In addition, researchers have proposed tailored devices and systems for remote physical collaboration. Leithinger et al. proposed an approach for collaborating remotely with an actuated pin-based display [18]. Feick et al. investigated the effects on collaborative work of sharing perspectives on physical objects using a robotic manipulator [7]. Saraiji et al. developed a system using a wearable robotic head and arms to achieve physical collaboration remotely [42]. However, there is space for research on interactions between humans and teleoperated machines that involve highly dynamic, high-intensity movements. We aim to contribute to an understanding of such interactive experiences through the testbed of sports.

2.2 Machines in Physical Activity

Human-scale robot arms that can share work spaces with humans have been used increasingly in recent years [13]. In addition to traditional (e.g., industrial) robot arms, researchers are also actively working on SuperLimbs, robotic arms that can be attached to a human body [49]. While their current capabilities and usages are limited, these may provide an opportunity to create machine-mediated teaming as surrogates of the human arm.

In the HCI field, there are methods to support creative activities such as 2D fabrication [41], sculpting [54], and painting [44] by allowing users to collaborate with specialized machines. More recently, similar approaches have been proposed in more dynamic activities such as throwing [21]. In addition, increased accessibility of robots and actuators allows researchers to utilize them to enhance the quality of user experience, such as by providing haptics [1, 47]. In these studies, the machine's actuation is automatically controlled according to the user's actions recognized with sensors. We investigate high-intensity physical interactions in which the user recognizes the actions of others and controls the machine's actuation.

2.3 Design of Physical Games with Technologies

Many researchers have tried to develop technologies for enhancing sports and physical game experience. One approach to enhancing the experience is to add visual effects to the environment using projectors [11] and head-mounted displays [6]. The use of enhanced visual information not only provides new experiences but also has the potential to improve game balance by assisting less skilled players, such as by the visualization of ball trajectories in ball games [12, 43]. On the other hand, Baudisch et al. pointed out the drawbacks of using an augmented reality (AR) based approach in physical sports and proposed a concept of a game played with an invisible ball by leveraging auditory feedback [2]. While these focus on designing experiences with augmented sensory feedback, we focus on extending the physical interaction with machine actuations. Approaches to designing experience using developed mechanical devices have also been explored. For example, sports designs have been proposed that use balls that can change their trajectory in the air with integrated quadcopters [34, 35] or gas jets [38] or can detect contexts of the game by embedded sensors [37]. These works focus on the development of devices or technologies that open up new sports designs. In this work, we define a new framework of MMT, which is different from these works, and focus on understanding the experience and design of MMT.

Researchers have also investigated the impacts of interactive games that require the user's physical effort and the methodologies for designing these games. The games are often referred to as exertion games, exergames, or movement-based games [25]. It has been shown that a well-designed exertion game can have positive effects on health [10, 15], social interaction [19] and game engagement [4, 19]. To design and analyze exertion games effectively, various guidelines and frameworks [8, 20, 22, 27] and perspectives for future investigations [23, 26, 28] have been proposed based on developed game examples. Like these studies, our goal is also to investigate guidelines for designing interactive games. However, we focus on the design of gaming systems in which people and machines physically interact and cooperatively work.

3 GAME AND SYSTEM DESIGN

As a concrete example of MMT, we developed an environment where BPs and MPs work in a mixed state, using tug-of-war as a testbed. Fig. 1 (a) shows an overview of the system framework. Our system consisted of a *machine*, which can provide human-scale pulling force, and at the end of the rope, a *handle device* with force sensors, and a *tablet interface* to control the machine output. Fig. 5 shows the overall system architecture. The main PC controlled the machines and received sensor data and MP input. The machine and the handle device were placed symmetrically in a straight line and physically connected with rope (i.e., the front side was connected to the handle device of its opponent, the rear side of the handle device was connected to the machine of its own side). In this section, we describe the details of our game and system design.

3.1 Game Design

3.1.1 General rules. The game using our system is played by four participants simultaneously. The two players of each team are divided into the roles of BP and MP. The BP holds the handle device and plays tug-of-war face-to-face with a physical opponent (i.e., the BP of the opposing team) at a certain distance(Fig. 3-b). The MP controls the machine by manipulating a tablet interface and collaborates with the BP. We defined the distance between the machines on each side as field size (Fig. 3-a). A team wins the game if they can pull the rope from the start position to their own side up to the goal position set at a specific distance (Fig. 3-c).

3.1.2 Definition of machine energy. To add a strategic element to the game, we defined a parameter named "machine energy" that indicates the total amount of force that the machine can provide during a game. This parameter was introduced to prevent the MP from constantly inputting the maximum force. The machine energy decreased in proportion to the force applied by the machine, and when it had run out, the machine could no longer provide the force during the game. In other words, the machine energy available during a game was limited, and the MP had to adjust the amount of force within the given machine energy for each game. The machine energy at the start of the game was determined through the pilot study described in the next section.

3.2 System Design

To provide human-scale pulling force to the rope according to the input of the MP's operation, we designed a machine which has a motor to wind the rope, as shown in Fig. 2. The machine was fixed in position behind the BP. We adopted a large-diameter brushless DC (BLDC) motor with a low reduction ratio. This motor was chosen for its back drivability and high torque output. To control the force applied to the rope, we controlled the current going through the motor.

To monitor each kind of force generated in the system, we designed a handle device with force sensors. A force sensor was attached to both ends of each handle device, and each player pulled the rope by grasping the grip between the force sensors. The front sensor was connected to the handle device of the opposing side, and the rear sensor was connected to the machine. Thus, when the pulling forces of the two teams are balanced, the value of the front sensor represents the combined force of the BP and the machine on the rope. The rear sensor represents the actual force of machine. Moreover, we calculated the force exerted by the BP by subtracting the rear sensor value from the front sensor value.

The MP used a tablet as an interface to operate the machine. They controlled the force presentation of the machine using the touch screen, as shown in Fig. 4. A vertical bar indicator (Fig. 4 (b)-1) showed the amount of remaining machine energy. When the indicator reached the bottom, the text 'EMPTY' appeared on the screen, and the machine stopped providing force. The MP was able

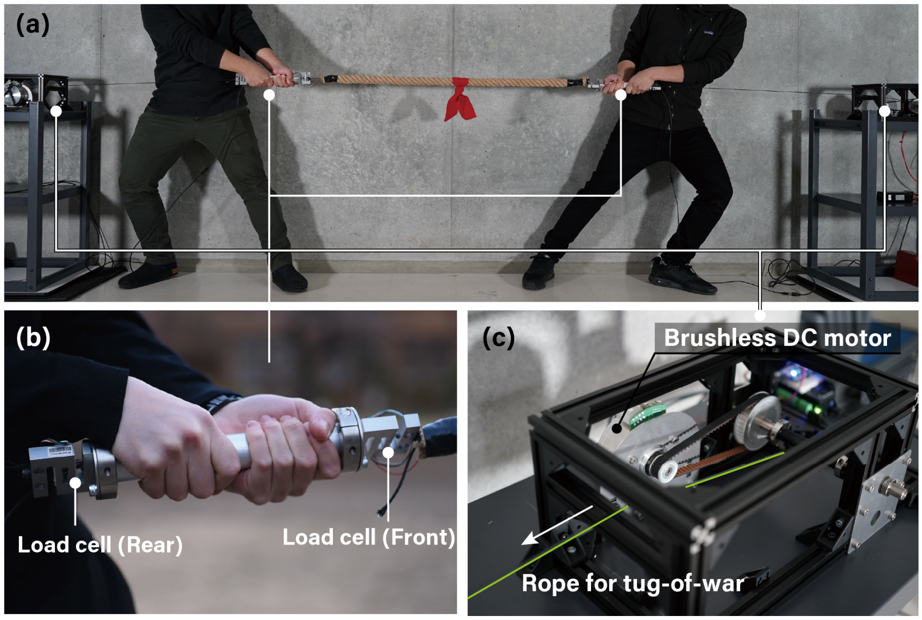


Figure 2: (a) BPs pull at the rope using the handle device. (b) The handle device has two load cells to measure forces at both the front and rear ends, which detects how each player is applying force. (c) A brushless DC motor can pull at the rope from behind each player.

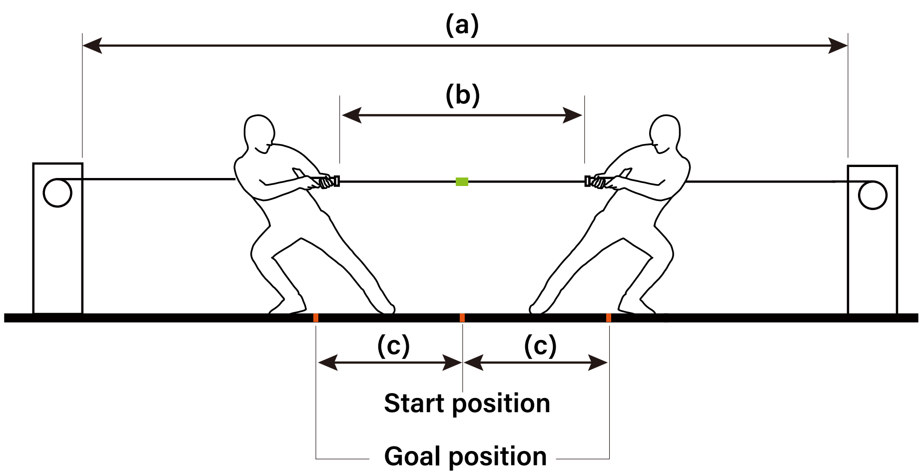


Figure 3: The field set up in our system, including (a) field size, (b) distance between BPs, and (c) distance from the start of the game until the winner is determined.

to control the amount of force in real-time by moving the horizontal slider (Fig. 4 (b)-2). The button (Fig. 4 (b)-3) is an activation switch that toggles the machine's standby state provided to prevent the MP's misoperation. The line graph (Fig. 4 (b)-4) allows MPs to monitor the control history for the previous four seconds.

3.2.1 Machine power. We defined "machine power" as the amount of force provided by the machine according to the MP manipulating the tablet. The maximum machine power was determined depending on the amount of current that the motor driver could control. When the motor power was at its maximum, the motor driver sent about 8.3A of current to the DC motor, and the motor transmitted about 2.0 N · m of torque to the shaft. According to our preliminary measurements, the force provided to the rope at the maximum machine power was about 300 N. The machine power was controlled to be proportional to a value inputted by the MP. The machine also provided a constant force to prevent slack in the rope. Thus, the force provided by the machine Fm is described as;

$$Fm = F_{max} \cdot R_{mp} + Fc$$

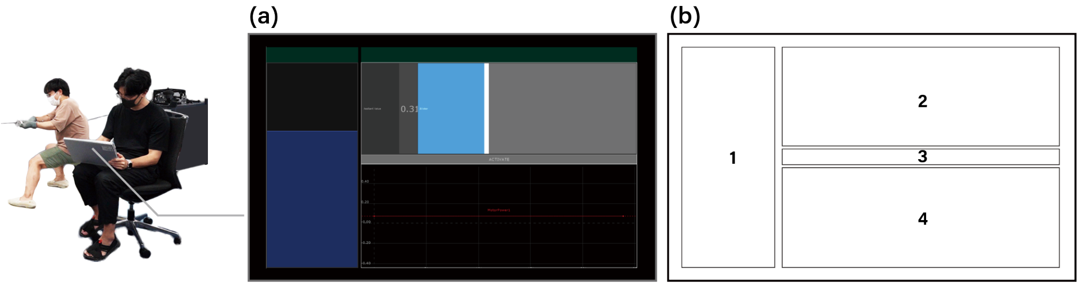


Figure 4: (a) GUI displayed on the tablet screen. (b)-1 shows the amount of machine energy remaining. (b)-2 shows the slider interface to control the machine's output power. (b)-3 shows an activation button to prevent MP misoperation. (b)-4 shows a line graph to allow MPs to monitor the control history for the last four seconds.

Here, F_{max} is the maximum machine power, R_{mp} is the value that the MP controls, and, F_c is the constant force.

3.2.2 Configuration of machine energy. The amount of machine energy [J] was set as the imitated amount of electric energy required to run the motor. Calculations based on the specifications of the DC motor we used showed that about 185 W of power was required to output the maximum motor power mentioned above. We used this amount of power as the reference for setting the total amount of machine energy that the MP could use during each game. Specifically, the input values of machine power sent from the tablet were monitored by the main PC at a refresh rate of 100Hz, and the amount of energy used was estimated in real-time. Then, this estimated energy consumption was subtracted from the machine energy given to the MP. When the computer detected that the machine energy was running out, the input value of motor power was not sent to the motor driver. Thus, given 1850 J of energy, the machine ran for 10 seconds if it continued to present the maximum power.

3.2.3 Calculating the rope position. The one-dimensional rope position was calculated by the encoders of the motors. We used this value to automatically detect the winner of games. We used a nylon paracord with a diameter of 4mm for the ropes that connected the handle device to the machine. The rope was wound by a shaft with a diameter of 10mm driven by the motor. Note that this was not completely accurate, as the nylon paracord was slightly elastic, and the force applied by the motor to the paracord fluctuated depending on the conditions of the match. However, it had sufficient accuracy to judge winners and losers.

3.2.4 System Architecture. Fig.5 shows the system architecture. The sensor data and MP input data were sent to the main PC (Windows 10 PC with Intel Core i7-10875H 2.3GHz CPU and an NVIDIA GeForce RTX 2080 Super Max-Q GPU), and were recorded with a 100Hz refresh rate. As shown in Fig. 5 (a), the rope tension was measured with the load cells (SC301A) and converted to digital data with an A/D converter (ADC), HX711. This data was received by Microcontroller (MCU), Teensy 3.6, and sent to the main PC to be monitored and recorded. The machine received control commands based on the MP input and controlled the motor output to wind the rope. As shown in Fig. 5 (b), MCU, mbed LCP1768, received the command from the main PC and controlled the motor current by sending values of PWM to a motor driver, ESCON 70/10 from MAXON, and received the encoder data to calculate the rope position.

4 USER STUDIES AND RESULTS

To understand a machine-mediated teaming (MMT) experience, we conducted a set of user studies where participants played tug-of-war games using our proposed system. After the games, the participants were interviewed and asked to verbally describe their experiences and strategies used during the games. The activities of the game and the discussions in the interview were video recorded. Our findings described in this paper included analyzing the transcriptions of the verbal responses and discussions during the game and interviews, and analyzing the participants' behavior during the game referring to the recorded video and the sensor data aptured by our system; throughout the authors iteratively viewed these recordings and decided to critical and important scenes and topics to be highlighted, following qualitative methods [9].

We initially conducted a pilot study to find out the appropriate settings for preparing the MMT experience. Specifically, we initially set the parameters (e.g., machine energy, goal position, field size, etc.) through internal discussions, observed the players' performances, and listed the parameters to be revised. Considering the findings from the pilot study, we conducted an exploratory user study (hereafter exploratory study) to understand how an MMT dramatically produces a tug-of-war game requiring strategy, tactics, and collaboration. After the studies, we analyzed how the revised settings contributed to the games in the exploratory study, and discussed implications for designing future MMT games.

4.1 Pilot Study

4.1.1 Game Settings. We set the duration of a game to one minute. If the winner was not decided within one minute, the team which had pulled the rope furthest to its own side won the game. The goal position was set at 50 cm behind the start position and the field size at 4.5 m. The machine energy at the start of the game was set to 3700 J; this was the value at which the machine was able to run for 20 seconds at maximum power. Participants played a total of five games, and the team that won three games first was declared the winner. However, we conducted all five games, even if the winner had already been decided.

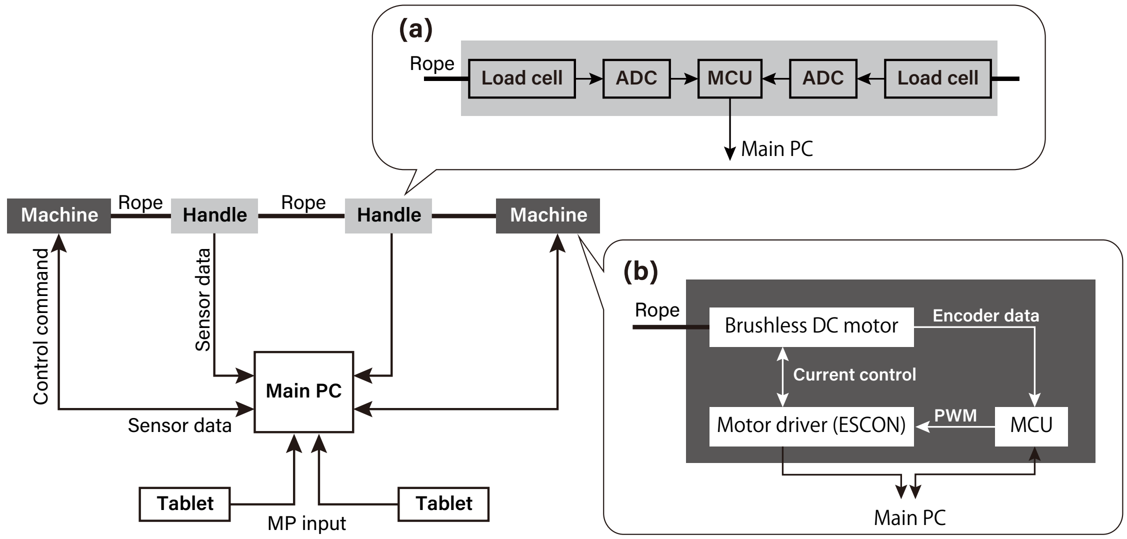


Figure 5: System architecture. The main PC controls the machine's actuation based on the MP input from the tablets, and monitors sensor data, including the rope tension and encoder data.

4.1.2 Participants. The user studies were conducted for a small number of participants due to COVID-19 restrictions. We recruited four naïve participants (two males and two females; aged 24 - 41, mean age 29.5 years old, $SD = 8.0$). No participants had a physical disability. The study protocol was performed in accordance with the Declaration of Helsinki. All participants signed a letter of consent after being provided with an overview of the user study and instructions. Participants were given a basic explanation of the workshop and signed a consent form. Of the four participants, the two males, who had the most minor differences in physique, were assigned to team A and team B as the BP (A-BP: height 172 cm, weight 67 Kg; B-BP: height 174 cm, weight 68 Kg). The remaining two participants (female) were randomly assigned as the MPs to each team (A-MP and B-MP). The teams and roles were the same throughout all games.

4.1.3 Procedure. Before the game started, we set up a training session to familiarize the participants with the system. In this session, participants were able to confirm the sequence of the game, how to operate the tablet, and the force feedback provided by the machine.

Each game was conducted according to the following procedure. Before the start of the game, the BPs of each team stood face-to-face by holdings their handle devices. Then, the main PC presented a whistling sound as the cue for the start of the game under the control of the experimenter. As soon as the whistling sound was presented, the BPs started to play tug-of-war, and the MPs were able to control the machine. The machine provided the pulling force according to the MP's real-time input while the machine energy remained. During the game, participants were not restricted in vocalization or communication and were free to talk to each other. When the rope reached the goal position, or when the duration of the game expired, a whistling sound was presented to indicate game end. At the same time, the machine stopped providing the force, and the winner of the game was judged based on the calculated position of the rope. After each game, there was an interval of one minute. During the interval, the participants were required to discuss strategies for the next game within their teams.

4.2 Results of the Pilot Study

We found issues that needed to be resolved in the machine energy and the goal position. First, we found abundant machine energy can have a negative effect on strategic coordination within a team. During the game, the MPs of the teams made little change to the power output of their machines from the maximum power. As shown in Table.1a, all five games ended within 20 seconds. Thus, the machine energy did not run out during the game, even if the machine kept providing the maximum force. Actually, we observed that the MP of each team kept the machine power at maximum for most of the duration. The reason for this was that the machine energy was abundant and there was no need to conserve it. For example, B-MP reported, *"The 20 seconds that the machine could drive at the maximum power was unexpectedly long."* When the force from both machines was always balanced, the game context depended on just the BPs' behavior. Therefore, we concluded that the machine energy at the start of the game should be revised downward.

Second, we found that the distance to the goal position was too short for the players to act strategically. For example, actions of relaxing the pulling force once and then pulling with momentum were rarely observed. We found that the participants felt a risk that if they reduced the pulling force even a little, it would directly lead to losing. A-BP reported, *"We couldn't implement the strategy of loosening once and pulling back. We expected that when we loosened up, the opponent would win because the distance to determine the winner is quite short. We felt if the distance to the goal is longer, the more strategy we could implement."*

Table 1: Score sheets of user studies ((a) pilot study, (b) exploratory study). The rightmost column shows the time taken for each game.

(a) Score sheet of the pilot study

Game ID	Team A		Team B	Time (sec)
1	win	-		0:18
2		-	win	0:15
3		-	win	0:15
4		-	win	0:04
5		-	win	0:13
Total score	1	-	4	

(b) Score sheet of the exploratory study

Game ID	Team C		Team D	Time (sec)
1	win	-		0:18
2	win	-		0:18
3	win	-		0:04
4	win	-		0:30
5	win	-		0:22
Total score	5	-	0	

In the exploratory study, to encourage strategic cooperation within a team, we changed two parameters, the machine energy at the start of the game and the distance to the goal position.

4.3 Exploratory User Study

Based on the pilot study, we changed the machine energy to 1850 J (i.e., half that of the pilot study) and the goal position to 100 cm (i.e., double that of the pilot study). To accommodate the change of goal position, we also widened the field size to 5.5 m. We anticipated that these improvements would lead to a variety of strategic behaviors and cooperation between BPs and MPs. All other game settings were the same as in the pilot study.

We recruited a different set of participants (four males; aged 25 - 35, mean age 28.8 years old, SD = 4.3; no physical disability). Two participants who had the most minor differences in physique were assigned to Team C and Team D as the BPs (C-BP: height 165 cm, weight 60 Kg; D-BP: height 170 cm, weight 60 Kg). They participated in the study with the same processes as in the pilot study.

4.4 Results of the Exploratory User Study

The results showed that the changes we made as a result of the pilot study were an improvement, and participants performed strategic cooperation. Table.1b shows the results of each game. In the exploratory study, except for the third game, at least one of the teams' machine energy ran out in the middle of the game. On the other hand, the length of each game tended to be longer than in the pilot study. These results suggest that, by increasing the distance to the goal position, the range and options of BPs' actions expanded, and MPs strategically controlled the output of the machine within the limited machine energy.

Hereafter, this section highlights the strategic games and describes the strategies and roles of the participants during the games.

4.4.1 Highlights. We highlight and describe the last two games (i.e., the fourth and fifth game) as the tightest games with strategic behaviors (see the supplementary video). Fig. 6 shows the notable events that occurred during the fourth and fifth games and the condition of the machine and rope during the games. From the observation of all the games, it seemed that C-BP was basically slightly stronger than D-BP. However, in the fourth game, Team D was conserving their machine energy and creating chances. In the end, both teams ran out of machine energy, and Team C won; however, it was a tight game that lasted 30 seconds. Conversely, in the fifth game, Team C made strategic use of machine energy. They had used little machine power by the middle of the game to conserve machine energy. Then, they also performed strategic cooperation in which the C-MP would adjust the machine power in response to the D-BP's cue with shouting. As a result, they won with machine energy remaining.

4.4.2 Players' Strategies and Roles. We found that the participants were aware of their roles and collaborated strategically. BPs tended to concentrate on the opponent in front of them and play tug-of-war as hard as they could, while MPs tended to assist BPs by watching the game situation. For example, D-BP said, *"Basically, I focused on the one-on-one battle between BPs."* C-MP also reported, *"I felt like I was assisting C-BP by adjusting the power of the machine to suit them, rather than controlling the match myself."* We confirmed that participants tried to strategically use the limited machine energy. For example, BPs not only applied strong force consistently but also repeated relaxing the force a little and then tugged vigorously. Similarly, MPs not only consistently output maximum machine force but also actively moved the slider of the tablet during the game. As feedback regarding these strategies, D-BP reported, *"In the first and second games, our team adopted a strategy of exerting a strong force at the beginning of the game, and in the latter three games, we adopted a strategy of gradually increasing the power of the machine. And by repeatedly tugging, we hoped that the opponent would be off-balance."* We also confirmed that the BPs and MPs communicated with each other. For example, the MPs had tried to share the amount of machine force with their teammate (e.g., discussing the pattern of machine force in the next game during the interval and showing the tablet screen during the game).

5 DISCUSSION

5.1 Implications for Designing an MMT

Based on the findings, we discuss three areas to consider when designing an MMT and human-machine systems.

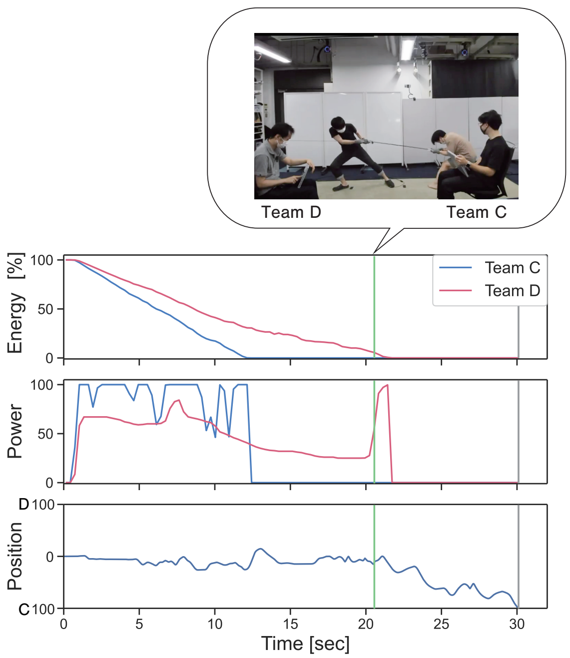
5.1.1 Machine stamina. The first point to consider is to design the *stamina* of the machine. This means introducing an accumulation of pseudo-fatigue into the machine, and defining the temporal effects of the machine's actuation on its subsequent actuation. We found that appropriate machine stamina can enhance strategy and add complexity to the game. Basically, a machine can continue to keep

(a) Event recording of the 4th game

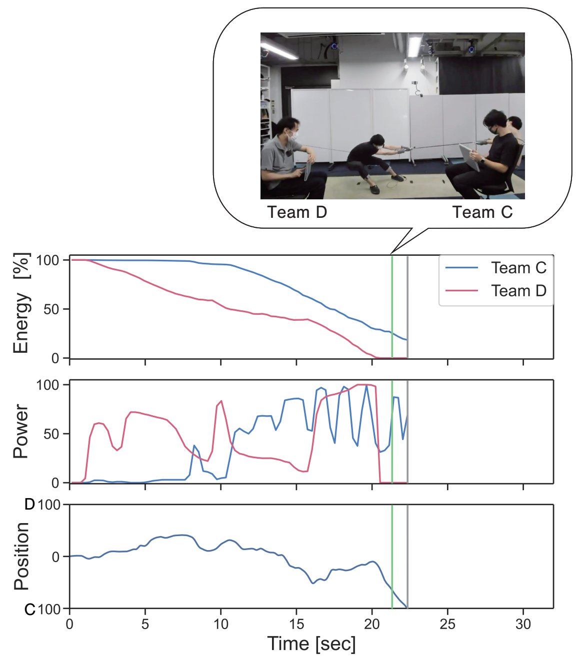
Time	Event
0:00	The game begins.
0:01	C-MP raises the machine power to around 100%. D-MP keeps it at around 60%.
0:06	MPs up and down the power as BPs' motion.
0:07	D-MP keeps the power below 50%. Team C has a slight lead.
0:12	Team C's machine energy runs out. D-MP keeps the power around 30%.
0:21	D-MP raises the power to 100%. Team D gains the lead.
0:22	Team D's machine energy runs out.
0:24	Team C regains the lead.
0:30	The game ends (Team C wins).

(b) Event recording of the 5th game

Time	Event
0:00	The game begins.
0:01	C-MP stays the machine power at almost 0%. D-MP keeps it at about 60%.
0:07	C-MP start to control the power. Team D has a slight lead.
0:11	C-BP starts to generate shouting, C-MP up and down the power according to the shouting. D-MP keeps the power around 30%.
0:15	Team C regains the lead.
0:16	D-MP raises the power to near 100% at once.
0:18	The two teams are even.
0:20	Team D's machine energy runs out.
0:22	The game ends (Team C wins).



(c) Recorded data of the 4th game



(d) Recorded data of the 5th game

Figure 6: Result of the fourth game (left) and the fifth game (right) in the exploratory study. The top table shows a summary of events during the game. The bottom graph is recorded data of machine energy (top), machine power (middle), and the position of the rope (bottom). The photo shows the game at the time of the green scene vertical line. The gray vertical indicates the time of the end of the game.

actuation for a long period of time without getting tired, as long as energy is available. Therefore, if the machine stamina is infinite, the MP may take the maximum output continuously, unlike the BP. This would mean that enjoyable and tactical aspects of the game, such as intelligently constructing strategies, would be missing, and the game would become a sport with little strategy. At the beginning of designing our system, we also thought it was necessary to design the stamina, which was designed by setting the machine energy, but the results of the user studies suggested that it would play a more important role than expected. For example, in the pilot study, we identified that the energy was in excess of the appropriate value, and the strategies of both MPs converged on always running the machine at maximum power, resulting in no strategic diversity. In the exploratory study, the energy was halved compared with the pilot study, and it was confirmed that strategies such as cyclic control of machine actuation and saving the energy in the early stages were generated.

On the other hand, our study indicates that there is still room for further improvement in how to design machine stamina. In our study, we only defined the total amount of energy that could be output as the stamina. However, we may expect more appropriate game design by incorporating metaphors of somatic limitation such as non-linearity between power output and stamina consumption and stamina recovery. Indeed, in the pilot study, the MPs tended to estimate the machine's contribution to the game higher than the MPs did in the exploratory study, although they performed less strategic actions. Similarly, the BPs also estimated the machine's influence as stronger in the pilot study than in the exploratory study, and rated it as equivalent to their own power. This is probably due to the fact that the total amount of energy that could be used with the machine was greater in the pilot study than in the exploratory study, even though the maximum power that the machine could output remained the same, and the machine could have more influence on the game. Therefore, identifying guidelines for defining the machine stamina that allows MPs to maintain their contribution to the game while ensuring strategic diversity is a challenge to be tackled.

Introducing the notion of machine stamina may contribute to an inducement of naturally cooperative behavior in general human-machine physical interaction, as caring about one's own stamina leads to caring about the teammate's stamina.

5.1.2 Action space. The second area regards the spaces in which the BPs and machines perform actions. This means that because the players' actions are highly dynamic, as opposed to existing static collaborations and tasks, the spatial positioning of humans and machines performing the actions needs to be designed more carefully.

For example, in the pilot study, we considered that the space between the BP and the machine was sufficient for the distance from the start position to the goal position. However, in the actual game, we observed several times that the BP pulled the rope towards the back diagonally, instead of naturally behind them. This was due to unconscious behavior to prevent contact with the machine in the event of an accident, such as the rope breaking. No such behavior was observed in the conditions of the exploratory study, in which the initial distance between the BP and the machine was slightly larger than in the pilot study. This suggests that the action space of the BP required for action should be larger than the space required to just perform the task, because it involves intense physical movement. We suggest that in designing an MMT based on existing sports, it is not only necessary to substitute the physical role of existing sports with machines in a straightforward manner, but also to design the field and the spatial arrangement of the BPs and machines accordingly.

Although models of physical distancing between people and machines [31] and the influence of machines on the spatial arrangement of people [39] have been investigated, our study sheds light on the spatial relationship between humans and machines from a new perspective, in an environment that requires more dynamic movement.

5.1.3 Explicit feedback. Thirdly, we argue for designing feedback that enables BPs to sense the behavioral information of machines and MPs. Initially, we assumed that BPs share the rope with the machine, and thus can indirectly sense some of the machine's output. However, the BPs reported that during the game, i.e., when they were concentrating on their own physical effort, they could hardly take into account how the machine was exerting its power, and could not communicate with the MPs. In other words, although we found that the MPs were adjusting the power of the machine according to the BPs action, it was difficult for the BPs to cooperate in a similar way. Therefore, to facilitate interaction and cooperation between BPs and MPs, we conclude that a system that provides real-time feedback to BPs on the state of the machine or the behavior of MPs is necessary. In addition, in the exploratory study, we observed that the MP manipulated the tablet so that it could be seen by the teammate BP, but the BP reported that he could not afford to look at the tablet screen during the game. This suggests that it will be necessary to present information to BPs in a way that does not rely on visual feedback. Interestingly, in the pilot study, the BPs reported that they could sense the amount of the machine power from the sound of the machine reeling in the rope. We conclude that auditory feedback and sonification of information may be a potentially useful information presentation approach, such as in [2]. We suggest that designing inducements for MPs to communicate actively may also be an important approach.

In traditional team sports, players subconsciously sense the presence and actions of others in various ways such as through voices and footsteps, but machines do not necessarily have such elements, and the information available to the BPs is not intuitively connected to their actual actions. Compared with research on feedback to the operator in teleoperated robots, explicit feedback design to collocated people has not been sufficiently investigated, maybe because it was assumed to be in a static situation such as conversation, such as in [40]. We conclude that our results clarify the issues that need to be addressed for future collaboration between humans and robots using physical bodies dynamically.

5.2 Extensibility of the MMT in Everyday Contexts and Other Games

Through our user study, we found that there is room for discussion in terms of how handicapping is designed, although we did not consider the issue of balancing the game in this study. In our study, we assigned two participants as the BPs so that the difference in fitness level would be the smallest among the recruited participants. Both teams then played the game under the same system conditions. While we considered this setting was a fair regulation, some users suggested adding handicapping to balance the game. Repeated loss of games may have led to this suggestions.

Handicapping is a popular approach used in conventional sports and games. Handicapping, if used appropriately, has the potential to excite not only the player but also the spectator. While there are some methodologies for handicapping design, such as in golf [48] and horse racing [3], how to set handicapping in a new sport so that each team has an equal chance of winning is challenging. On the other hand, in everyday sports, one of the ways to enjoy them is for players to design their own rules or settings. In our system, the players were not allowed to modify the rules and settings, but modifications by the players may make the game more balanced or more exciting depending on the situation. Thus, it could be a promising avenue to extend the system to include parameters that can be adjusted by the player to encourage the players to design their own rules. For example, in this case, we could prepare an interface that allows the user to freely decide the total amount of machine energy. Additionally, the field could be extended to make goal positions asymmetrical, or to increase the number of BPs on one side.

The machine we developed was fixed to the field and had only one actuated degree of freedom (DoF). However, our MMT concept can be applicable to a variety of machines and robots, such as those with multiple DoFs [13], mobility [53], or wearability [42]. Utilizing these machines, there will be a possibility of developing various forms of games. The implications described in the previous section may also be helpful for designing MMT games with such machines, although they will have their own limitations and considerations. We conclude that various practices and discussions will be necessary for further investigations of MMT, and accumulating MMT examples and findings in various forms will play an important role in clarifying future design guidelines.

Furthermore, the interface operated by the MP can take various forms. The machine was controlled with a tablet interface in our study. This interface allows people who have different fitness levels, such as adults and children, and paraplegics and able-bodied people to participate in the game at the same time. Our study suggests that an MMT can give users a sense of belonging to a team, as the MPs reported feeling frustrated when their team lost. While the tablet interface is easy to use, sensing and human augmentation technologies such as brain-machine interfaces [16] and eye tracking [5] could be used to enable even severely disabled people to participate in physical and interdependent sports.

6 CONCLUSIONS

We proposed a form of mixed human-machine sport, named MMT, with the aim of creating a team sport that can offer an interdependent physical exertion experience. In the MMT, we defined two types of players: 1) the BP, who uses their own body to perform physical movements in a game, and 2) the MP, who participates in the game by controlling specialized machines from outside and performing movements. We developed a system that achieves our proposed concept based on tug-of-war. Our system enables the MP to participate in the tug-of-war game with a machine we developed, which can present human-scale pulling force, and a tablet interface to control the machine action. To validate the proposed concept and reveal insights into designing MMT experiences, we conducted two user studies, the pilot study and the exploratory study. We were able to observe the development of strategies such as the adjustment of the machine power depending the situation in the new form of sport and gain several insights through interviews. Based on the findings, we discussed how our study can contribute to related research, including three perspectives that should be considered in future MMT design: 1) machine stamina, 2) action space, and 3) explicit feedback design. We also discussed the extensibility of MMT, including the game modification by the players and applications to other gaming contexts. We hope that this work will inspire other researchers to further investigate dynamic physical interactions and augmented experience enabled by machine mediation.

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