IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 26, 2021, accepted February 7, 2022, date of publication February 11, 2022, date of current version February 22, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3151094

Joy-Pros: A Gaming Prosthesis to Enable Para-Esports for Persons With Upper Limb Deficiencies

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This work was supported by the Japan Society for the Promotion of Science KAKENHI under Grant 21H03475.

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Internal Review Board of the University of Tsukuba, Faculty of Systems and Information Engineering under IRB Approval No. 2021R521.

ABSTRACT We present an investigation on game controller technology to enable para-esports. First, we present a review of the related literature on the information capacity of the human motor systems in pointing tasks and the evaluation of gaming controllers as pointing devices. Then we propose design criteria for controllers to enable para-esports in terms of target user, controller throughput, cognitive load, and comfort. Finally, we introduce the proposed controller with its rationale and functionality. We argue that the proposed controller is suitable to enable para-esports for persons with upper limb deficiencies because it enables bimanual control of video games like conventional controllers, and because of the achievable throughput and control dimensionality. The conducted experiments address the performance of the developed controller in terms of throughput and latency. A qualitative evaluation addresses the perceived usability, fatigue, and satisfaction of the users when using the prosthetic controller. We conclude that similar to para-sports, para-esports will have to be organized in classes that consider the game type and the type of physical disability of the athletes, and each class will require a controller suitable for its content and participants.

INDEX TERMS Para-esports, prosthetics, human augmentation.

I. INTRODUCTION

Esports are gaining increasing popularity around the globe. In 2020 the viewership of esports is estimated to have reached 495 million viewers, an 11.7% increase over the previous year, and it is expected to reach 464 million in 2023 [1]. With increased viewership also comes increased participation, and an increased need to consider inclusively [2] and the ability of persons with different bodily conditions to participate in the sport.

Upper limb amputation or deformation limits a person's ability to participate in a variety of activities that require hand dexterity. One such activity is to play video games for leisure or competitively as in esports. The majority of upper limb loss cases happen unilaterally, with 61% of the cases with transcarpal amputation, 12% with transradial amputation, and 2% with wrist disarticulation [3]. This amounts to 75% of persons with amputation having some level of a remaining forearm, which can be the initial target for para-esports with specialized game controller technology.

Video game controllers are designed to be used bimanually, whether in console games such as PlayStation, XBox, and Switch, or in PC games using a mouse and a keyboard. In the case of any unilateral hand or forearm deficit, the player will suffer a handicap that severely impacts their ability to play the game competitively, or play the game at all. To solve this issue a new game controller is needed. Such a controller should ideally enable the same level of performance for a person with a physical disability that a traditional controller can provide for a non-disabled person. In this work, we set to investigate and develop such a controller.

Accessibility controllers exist in the form of one-handed controllers [4] that condense all the possible control actions into one hand, or sparse controllers [5] that disperse the

The associate editor coordinating the review of this manuscript and approving it for publication was Giuseppe Desolda.

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control actions into multiple input units which can be used in a variety of arrangements. Both these types of controllers provide improved accessibility to the game control but compromised performance due to increased cognitive load, reduced effective control dimensionality, or reduced effective throughput. Alternative control methods using optical cameras such as the Microsoft Kinnect, or Playstation Move can also be used to enable persons with upper limb deficits to play a video game, but these controllers were found to have considerable disadvantages to the user in terms of movement time and throughput [6]. For para-esports, it is clear that controllers with higher performance are needed.

We have developed a new gaming controller for persons with upper limb deficiencies (figures 1 and 3). The developed controller, named Joy-Pros (Joy-Prosthesis), uses the forearm or the remaining stump of a person with an amputation as a pointing device, and distal click buttons, EMG triggers, or alternate click buttons to enable bi-manual game control (figure 3). We argue that the proposed controller is suitable to enable para-esports for persons with upper limb deficiencies due to the achievable throughput and control dimensionality. We also argue that making the controller in the form of a prosthesis will result in a better embodiment of the in-game control actions. In this paper, we present the Joy-Pros and the rationale behind its design. We present evaluation experiments of the throughput, movement time, and latency. Lastly we present a qualitative evaluation of the participants' perceived usability, fatigue, and satisfaction when using the prosthetic controller.

The objective of this work is threefold: 1. to provide a brief review of game controller throughput evaluations. 2. to lay out some design criteria for game controllers suitable for para-esports. 3. to develop and verify the proposed prosthetic game controller.

II. LITERATURE REVIEW

A. FITTS' LAW

In 1954, Paul M. Fitts [7] investigated the information capacity of the human motor system in controlling the amplitude of movement. In his work, Fitts expanded the use of information theory to the human motor system. In doing so he devised the Index of Difficulty (IoD) as a measure of the difficulty of a target selection task, and the Index of Performance (IoP) (also referred to as ThroughPut, TP) as a measure of human performance. These indexes are known as the Fitts' law.

Fitts' law is formulated as follows: the index of performance IP, or throughput TP, is obtained by dividing a motor task's index of difficulty ID by the movement time MT to complete the motor task.

$$IP = ID/MT \tag{1}$$

ID is measured in bits and MT is measured in seconds, therefore the throughput is measured in bits per second (bps). The index of difficulty ID depends on the target width and target amplitude. One of the common forms of ID is the shannon formulation which is used in human-computer interaction as follows:

$$ID = log_2\left(\frac{D}{W} + 1\right) \tag{2}$$

Fitts' Law was also adopted in the IS0 9241 Part 9 Standard and have been used in the literature to evaluate pointing devices [8]–[10], evaluate various game controllers against each other [6], [11], [12], evaluate different body parts performance in pointing tasks [13], and evaluate the effect of various parameters such as control-display gain, latency, and jitter on the pointing task [14], [15].

B. VIDEO GAME CONTROLLER THROUGHPUT

Video game controllers are commonly investigated in the literature as pointing devices using Fitts' Law [6], [11], [12]. Gareth *et al.* [11] compared the performance of a computer mouse, the Steam controller, the PlayStation DualShock 4 controller, and a Touchpad, and found that the computer mouse (3.99 bps) significantly outperforms the other controllers in terms of throughput and movement time. The touchpad (2.27 bps) and the steam controller (2.2 bps) outperformed the DualShock4 (1.92 bps), which uses thumbsticks for pointing.

Natapov *et al.* [12] compared classic video game consoles controllers (the XBox 360 controller and the PlayStation 3 controller) against the computer mouse and the Wiimote controller. The classic controllers use thumbsticks for the pointing task, while the Wiimote controller uses the forearm and wrist posture for pointing. Their measurement of throughput showed the mouse to be superior (3.78 bps), and the Wiimote (2.59 bps) to be better than classic controllers (1.48 bps).

Zaranek *et al.* [6] added some modern gaming input devices based on optical cameras to the comparison list. The compared devices were the computer mouse, the classic controller, the Kinect camera (XBox), and the Move camera (PlayStation). Their investigation showed the mouse (∼7 bps) and the controller (∼5 bps) were superior to the camera-based input devices; Kinect (∼1 bps) and Move (∼2 bps).

C. VARIATIONS BETWEEN DIFFERENT BODY SEGMENTS

In the above-mentioned studies, Fitts' Law is used to compare the performance of different controllers. Fitts's Law can also be used to compare the performance between different body segments used for the pointing task, or different users.

Balakrishnan and MacKenzie [13] investigated the difference between fingers, wrist, and forearm in controlling a computer courser, under the hypothesis that the fingers will outperform other body segments due to higher bandwidth in the underlying muscle groups. The results of this work, counter to the initial prediction, showed that the fingers (2.96 bps) under-performed the wrist (4.08 bps) and the forearm (4.14 bps) in the pointing task. These results are very valuable for the work presented in this paper because they show that with appropriate technology, a person without

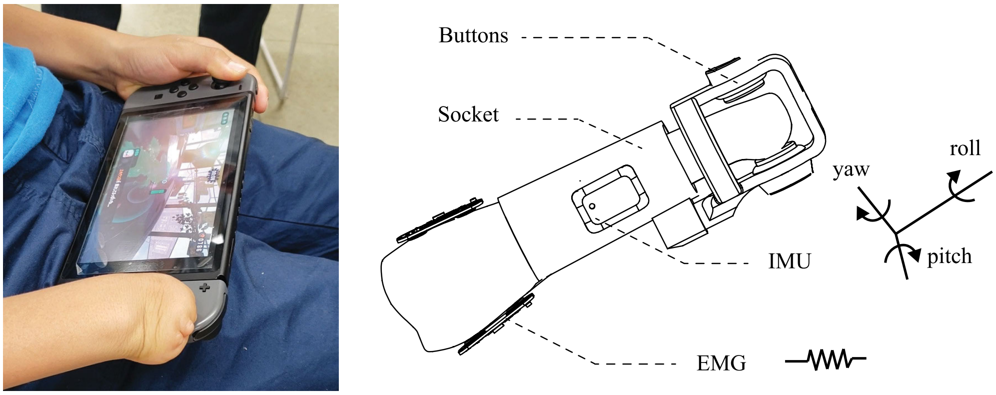


FIGURE 1. Left: a young person with unilateral hand deficiency playing video games. Right: the concept of the proposed prosthetic controller for para-esports.

fingers and without a wrist joint can still obtain good pointing (control) performance in a video game.

Chen *et al.* [14] also investigated the difference among the wrist, elbow, and shoulder joints when used in the pointing task. Their results showed that the wrist and elbow joints achieved higher throughput than the shoulder joint.

D. VARIATIONS DUE TO DIFFERENT CONTROL PARAMETERS

Variations in a controller's throughput can also emerge from the controller parameters [14], or from system impurities such as latency and jitter [15].

Chen *et al.* [14], investigated the effect of the control-display gain on the pointing task. The control-display gain is the coefficient that maps the movement of the pointing device to the movement of the display pointer. They investigated gain values of 0.6, 1.0, and 1.7, and reported that the 0.6 and 1.0 gains to produce higher throughput than the 1.7 gain.

Teather and Pavlovych [15] investigated the effect of adding artificial latency and spatial jitter to the tracking task using a computer mouse. In their investigation, they found that adding 40 ms of artificial latency to the mouse courser reduced the throughput from 4.68 bps to 4.17 bps, and adding 190 ms of artificial latency degraded the throughput significantly down to 2.35 bps. This work shows that minimizing the latency of the pointing device is essential for obtaining optimum throughput. On the other hand, their investigation also showed that spatial jitter has a much less severe effect on the measured throughput, less than 0.01 bps of difference.

E. ACCESSIBILITY CONTROLLERS

Several researchers have developed video game controllers for persons with physical disabilities. One of the common approaches explored in the literature is devising a sort of hub or interface device, to which traditional game controllers, off the shelf sensors, switches, buttons, and joysticks can be connected alike [5], [16], [17]. This approach helps each individual to map the controls of a video game to an arrangement of input modalities to their liking. The latest input device in this category is the XBox adaptive controller from Microsoft [18]. The XBox adaptive controller serves as an accessibility controller and enables the user to connect external buttons, switches, joysticks, and analog input devices, allowing for a wide variety of input arrangements.

Another approach is to develop one-handed controllers that enable flexible control functions. An example of this approach is the One-Handed Controller (OHC) developed by Maggiorini *et al.* [19]. The OHC uses one joystick with a touch screen panel. The touch screen can be set to display and accept a variety of inputs, which puts a variety of game controls in easy reach of the user.

F. PLAYER PERFORMANCE

Research on player performance in esports is largely concerned with analyzing player and team performance from game recordings [20], and building predictive models from player/team gameplay data [21], [22]. Some research also investigate the players' social behaviour, or social computing, in Massively Multiplayer Online Games (MMOGs) [23].

The player performance from the motor performance perspective is of more interest for enabling para-esports. Khromov *et al.* [24] compared the usage difference of mouse buttons and keyboard among newbies, low-skill amateurs, high-skill amateurs, and professionals. Their results showed differences in the usage and duration of the mouse action button and keyboard navigation keys (WASD) among the groups. Although they did not measure the throughput in their work, these findings are important for para-esports since they demonstrate that the control skills can be quantified and investigated between amateur gamers and esports athletes. If such observations persist with a new controller usable by persons with physical disabilities it can be inferred that such a controller does not interfere with the skill gap between different players, and thus provides a fair competitive platform for all the players.

III. DESIGN CRITERIA

The previous works on accessibility game controllers focused on providing alternate methods of input for persons with physical disabilities (Section. II-E). For a game controller to be suitable for para-esports it needs to be not just accessible, but also capable of high performance control. In addition it should afford adequate learnability headroom for the users to improve their skills through practice. In this section, we suggest four design criteria for para-esports enabling game controllers.

CONTROL DIMENSIONALITY

To introduce the design criteria we first have to familiarize the reader with the concept of Control Dimensionality (CD). CD is a method to measure or represent a game's control complexity [25], [26]. CD scores can be calculated by assigning a score for each executable action and summing the result. Scores can be assigned as below [26]:

- One dimension movement (left-right) CD = 1
- Two dimensions movement (left-right, up-down) CD = 2
- Three dimensions movement (left-right, up-down, in-out) CD = 3
- Additional movement dimension (strafing, acceleration, etc.) CD = 1
- Embedded action (jump, attack, etc.) CD = 0.5

An illustration of CD distribution in different types of controllers is shown in figure 2. In terms of CD, a good controller design should have an adequate CD score for the games intended to be played by the controller, and a good balance of CD scores for the right and left hands. The majority of PC and console games are controlled with two hands. PC games are controlled with a keyboard and a mouse, XBox, Play Station, and Nintendo console games are controlled with their respective two-handed controllers.

In first-person and third-person games where the player controls one in-game character. The left hand is usually used to navigate the space: using the left joystick or the WASD keys. The right hand is usually used to direct the character's heading in space: using the right joystick or the mouse's 2D relative position. Thus for either hand the CD score is 3 or 4.

In multiplayer online battle arena (MOBA) games the character's navigation and orientation are merged into one control action: using a joystick or the mouse. Therefore, also in this case each hand comprises a CD score of 3 or 4, but the left hand's CD is composed of many embedded actions, while the right hand's CD is a two-dimensional movement (CD = 2), and fewer embedded actions.

A. CRITERIA 1: TARGET USERS

Para-sports are designed with the particular type of physical disability of the athletes in mind. For example, wheelchair basketball is designed for wheelchair users who have functioning arms, therefore, persons with upper limb loss or deformity can not competitively participate in wheelchair basketball. Similarly, para-esports should be organized in classes that consider the game type and the type of physical disability of the athletes.

In the case of this work, the target users are persons with unilateral upper limb deficiencies. The targeted demographic includes persons with acquired or congenital finger loss or deformation, wrist dis-articulation, and trans-radial forearm loss. The target games are first-person shooters, third-person shooters, and MOBA games. Therefore, the controller should provide a CD similar to a computer mouse on the deficit side arm, assuming the intact-side arm can be used to operate the keyboard. Additionally, the achievable throughput by a group of target users should be considered in contrast to intact users.

B. CRITERIA 2: CONTROLLER THROUGHPUT

Video games, including the ones adopted in esports, are designed with consideration of a certain amount of throughput achievable by the game controller. Therefore, the controller for para-esports should be able to provide adequate throughput to play the game competitively, with headroom for the player to improve their performance through practice.

For example, in the case of this work, the authors elected to use the forearm as the pointing device. This is based on previous research [13] which had shown that the forearm shows higher or equal performance to the fingers and the wrist in a pointing task in terms of throughput.

C. CRITERIA 3: COGNITIVE LOAD AND CONTROL TASK

The cognitive load for a controller as an interface is related to the dimensionality of the controller, and the number of control actions per hand. While it is possible to condense the game control functions into one-handed controllers, this will inevitably affect the users' ability to coordinate their actions in the game, and their maximum action-rate in action intensive games.

The game controller for para-esports should provide adequate, but not excessive, control channels on each limb to enable dexterous control of the game and leave headroom for players to improve their performance through practice.

D. CRITERIA 4: COMFORT

The comfort of the controller also affects the control performance during longer play sessions. The comfort of the controller during a play session and the possibility of deteriorated performance should be considered in the design of the controller.

IV. SYSTEM OVERVIEW

Here we present the Joy-Pros controller: a video game controller that can be worn as a prosthetic device on the forearm. The Joy-Pros uses the forearm as a two-dimensional pointing device, and distal mounted click buttons, EMG triggers, or alternative click buttons for embedded actions. Here we present the rationale for these design choices, and how they can improve the control performance for persons with upper limb deficiencies.

An overview of Joy-Pros and its components is shown in figure 3. The Joy-Pros is worn around the forearm, just like a prosthesis, using a socket simulator (Pro Cuff, TRS,

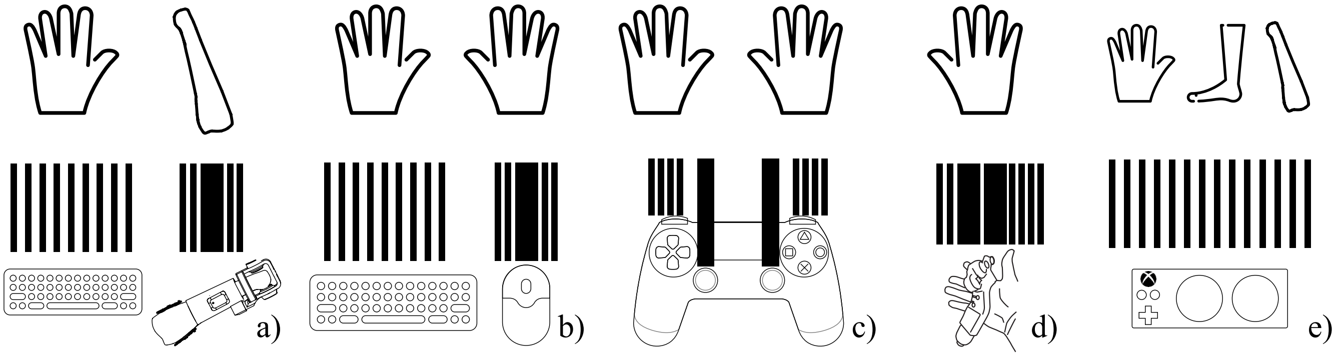


FIGURE 2. Comparative illustration of control dimensionality among: a) the proposed controller (Joy-Pros) used in combination with a keyboard, b) a computer mouse and keyboard, c) a gaming console controller, d) a one-handed accessibility controller, and e) a sparse accessibility controller.

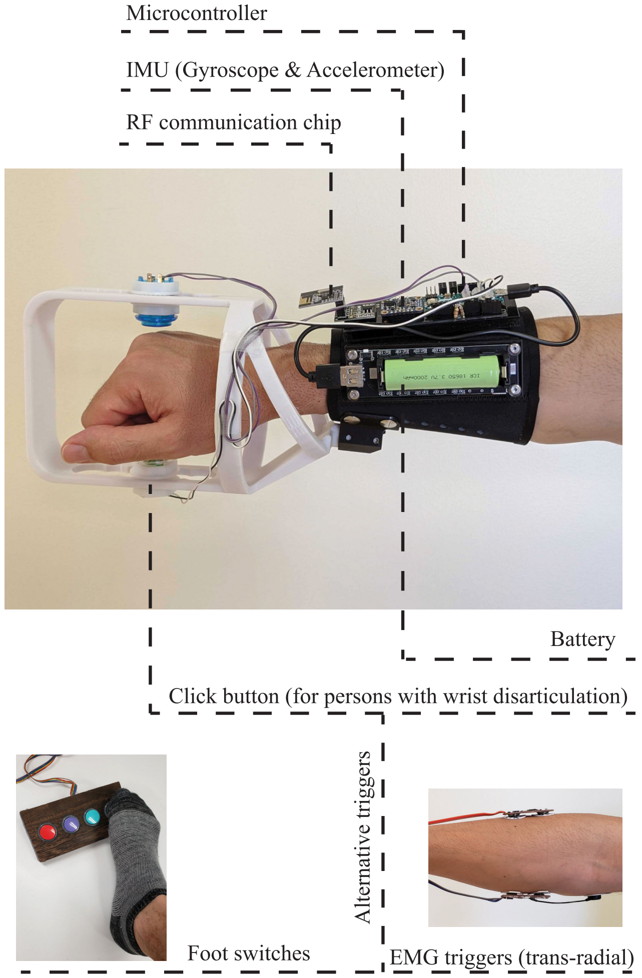


FIGURE 3. Overview of Joy-Pros and its components.

Colorado, USA [27]). The socket simulator is equipped with a BOA constrictor, thus it can adapt to a variety of forearm sizes. An adult version and a pediatric version of the socket simulator were prepared for Joy-Pros. Two click buttons are mounted distally to the socket simulator with a 3D printed frame. These buttons are intended as embedded action buttons for persons with remaining palm and wrist degrees of freedom. The position of the buttons can be adjusted to the user's preference. The distal buttons can be replaced with EMG triggers from the forearm muscles, or footplate buttons depending on the user's condition. The electronics and battery are mounted to the socket simulator as shown in figure 3. The electronics consist of a microcontroller (Arduino MICRO), an inertial measurement unit (IMU) (BNO055, Bosch Sensortec ©), and an RF communication chip (nRF24L01+, Nordic®Semiconductor).

A. OPERATION

The operation of Joy-Pros is illustrated in figure 4. The system comprises the Joy-Pros unit, a receiver unit, and the host PC or gaming console.

The microcontroller of the Joy-Pros acquires three-axis gyroscope and three-axis accelerometer readings from the IMU at 100 Hz. The microcontroller then compensates for the roll angle of the forearm using the accelerometer data. The compensated gyroscope readings for the pitch and yaw are then converted to relative horizontal and vertical movement. At the same time activation status of the distal buttons, EMG triggers, or footplate buttons is acquired through digital or analog inputs of the microcontroller. Movement data and trigger data are packaged and streamed to the receiver unit through RF wireless communication at 2 MBPS / 100 Hz package transfer rate. In the case of playing a game on a PC, the receiver unit converts the movement data to mouse courser commands, and the two trigger signals to the left mouse button and right mouse button presses. Mouse button double click, and click and hold are also processed by the receiver unit. Mouse move commands are streamed from the receiver unit to the game PC through a wired USB connection. Data is also streamed from the receiver unit to the gaming console at 100 Hz.

B. CALIBRATION

The IMU is mounted on the socket simulator with one axis aligned co-axially with the forearm. Thus, pronation and supination of the forearm are considered as roll angles. In this way, the pronation and supination of the forearm are compensated for as mentioned in IV-A.

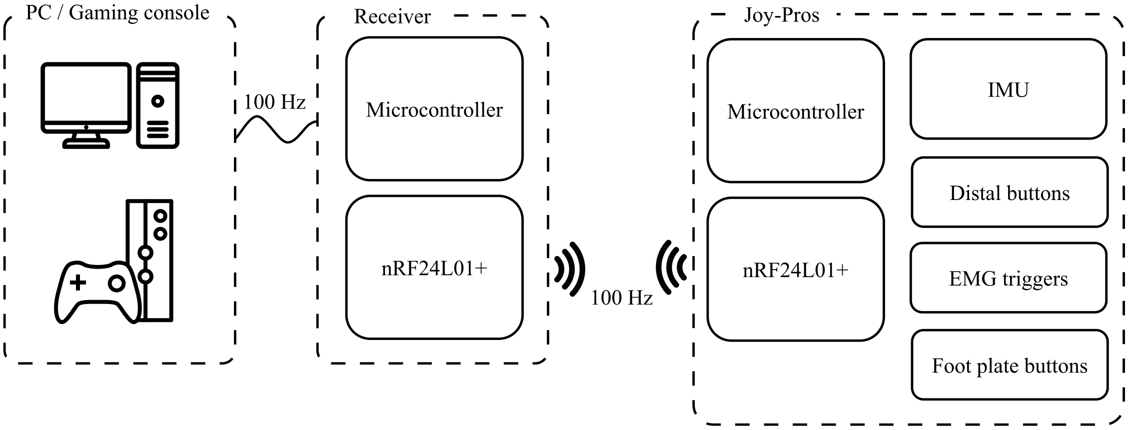


FIGURE 4. Diagram of the connections between Joy-Pros, the receiver, and host PC or gaming console.

The gyroscope of the IMU used in Joy-Pros (BNO055) automatically calibrates itself by detecting periods of inactivity and zeroing its readings to compensate for drifts. Other than the automatic calibration, the factory calibration of the IMU sensor is used in the current prototype. The position of the distally mounted buttons can be adjusted manually. The EMG triggers sensitivity can be adjusted manually through gain modification variable resistors on the EMG sensor boards.

V. EXPERIMENTS

We conducted a set of quantitative and qualitative experiments to evaluate the performance of Joy-Pros in relation to a common gaming controller. The experiments were designed to test the basic performance of Joy-Pros (throughput and latency) and the subjective evaluation of users during an in-game task. The experiments are listed in Table. 1. The intact participants were recruited from our local organization, and the end user was recruited from the University Hospital in collaboration with the physical rehabilitation department. The experimental procedures were approved by the Internal Review Board of the University of Tsukuba, Faculty of Systems and Information Engineering (IRB approval: 2021R521).

A. THROUGHPUT

This experiment measures the throughput of Joy-Pros compared to a PC gaming mouse and a game console controller. We used a free software developed by Scott MacKenzie [28] (GoFitts) to conduct the test. The tested devices were a computer gaming-grade mouse (Logicool G403 HERO), Joy-Pros, and the XBox one controller. The pointing task in GoFitts was configured as follows: Task Type: 2D, Selection method: Dwell time, Dwell time: 200ms, Amplitudes: 200, 400, 600, Widths: 40, 80, 120. The dwell time selection method was selected to exclude the effect of different methods of selection from the results. The amplitudes and widths were decided by the experimenter after initial tests to fit the screen size of the computer used in the experiment.

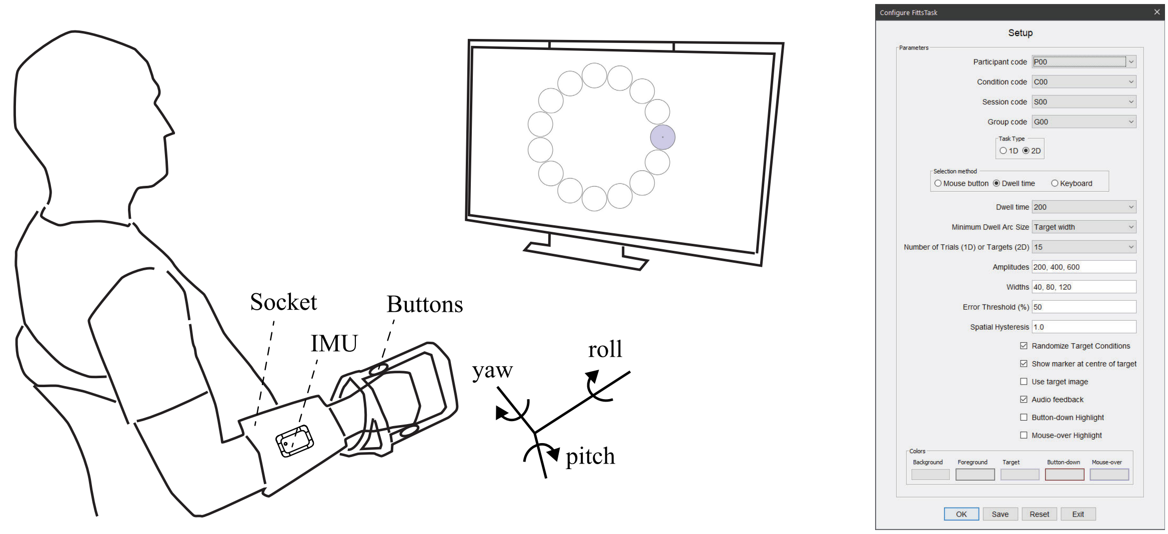
A laptop computer with a 15-inch screen size was used in the experiment. The screen resolution was set to 1920 × 1080 pixels, and the scaling set to 100%. Participants were seated comfortably in front of the computer at the normal range of laptop use. The setup is illustrated in figure 5. The intact participants were 11 healthy young adults, 9 males and 2 females, and they were all right-handed. The intact participants were asked to perform the pointing test with the computer mouse, the gaming controller, and the Joy-Pros; once for each. Each participant was given a few minutes to practice each of the tested devices and the procedure of the Fitts' task. They participants' age range was 21 to 35, and they were all familiar with using a PC mouse and gaming controller. The end user was a 28-year-old male. He underwent an amputation of the right hand fingers due trauma after a traffic accident. The end user was asked to perform the pointing test only with the Joy-Pros since he was not able to use the PC mouse or the gaming controller. The end user performed the pointing test four times in four different sessions spaced two weeks apart. This was to evaluate the learning effect of Joy-Pros, and to validate the consistency of the obtained results since only one end user was recruited.

1) RESULTS

The results of throughput and movement time measurements are shown in figure 6. The throughput measurement for the typical users (N=11) was 4.54 ± 0.52, 2.48 ± 0.166, and 2.19 ± 0.4 bps for the computer mouse, the Joy-Pros, and the gaming controller respectively. The movement time measurement for the typical users (N=11) was 663.15 ± 68.15, 1127.74 ± 75.67, and 1248.5 ± 235.36 ms for the computer mouse, the Joy-Pros, and the gaming controller respectively. The measured throughput with Joy-Pros when used by the end user was 2.41, 2.55, 2.75, and 2.98 bpsec, and the measured movement time was 1196, 1080, 1082.4 and 939.9 ms, for the four conducted sessions, respectively. The learning effect was calculated as percentage improvement in throughput between subsequent sessions and the first session. The results are shown in figure 7. The values of the learning effect were

TABLE 1. The conducted experiments, compared devices, and number of participants.

Experiment	Compared devices	Participants	End user
Throughput	PC mouse, Joy-Pros, Console controller	11	1
Latency	PC mouse, Joy-Pros	-	-
In-game task / Questionnaire	Joy-Pros	7	1



Setup

Parameters

Participant code P00
Condition code C00
Session code S00
Group code G00

Task Type
○ 1D ● 2D

Selection method
○ Mouse button ● Dwell time ○ Keyboard

Dwell time 200
Minimum Dwell Arc Size Target width
Number of Trials (1D) or Targets (2D) 15
Amplitudes 200, 400, 600
Widths 40, 80, 120
Error Threshold (%) 50
Spatial Hysteresis 1.0

☑ Randomize Target Conditions
☑ Show marker at centre of target
☐ Use target image
☑ Audio feedback
☐ Button-down Highlight
☐ Mouse-over Highlight

FIGURE 5. The experimental setup for evaluating the controller throughput.

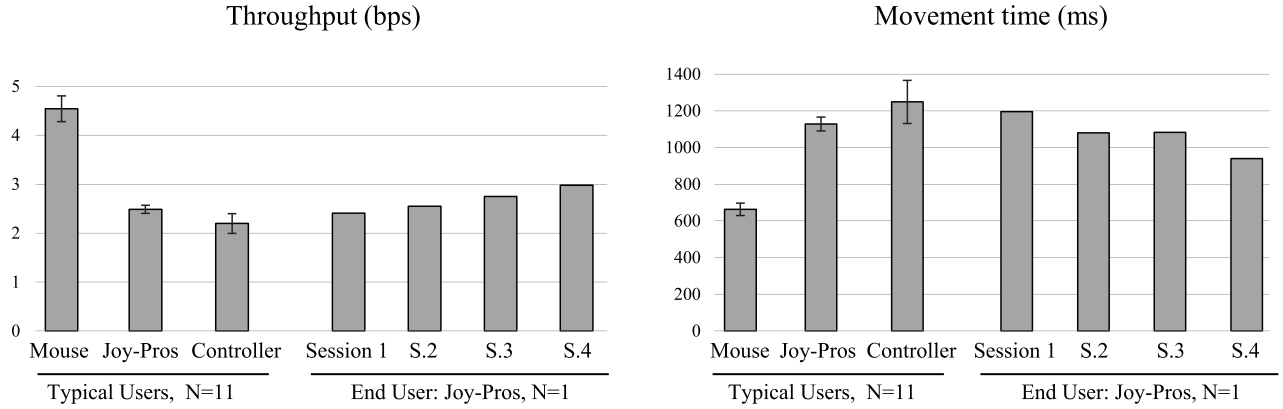


FIGURE 6. The average throughput for the all the participants using the gaming mouse, Joy-Pros, and game controller.

5.8%, 14.1%, and 23.65% for the second, third, and forth sessions respectively.

B. LATENCY

This experiment measured the relative difference in latency introduced by the Joy-Pros compared to a PC gaming mouse. For this purpose, we devised a setup in which the output of Joy-Pros and the PC gaming mouse can both be transformed to analog signals and recorded simultaneously by an ADC board at 1KHz. The Joy-Pros and the PC gaming mouse were physically fixed together using hot glue and repetitively dragged across a mouse pad in the lateral-medial directions with respect to the user. The recorded data of the horizontal axis was then similar to a sine wave for both of the devices. The data was then processed in MATLAB and the delay difference between the peaks of the sine wave-shaped trajectories were extracted. This difference represents the relative delay difference of the Joy-Pros compared to the PC gaming mouse, which is considered as the ground truth. An illustration of the experiment is shown in figure 8. The measured latency was 49.75 ± 4.9 ms.

C. IN-GAME TASK/QUESTIONNAIRE

The last experiment conducted in this work consisted of an in-game task that needed to be achieved by the participants. Seven intact young adult males and the end user of the throughput experiment V-A participated in this experiment. The purpose of this experiment was not to capture the performance variables of the users but to expose them to a relatively longer gaming session with Joy-Pros. The game

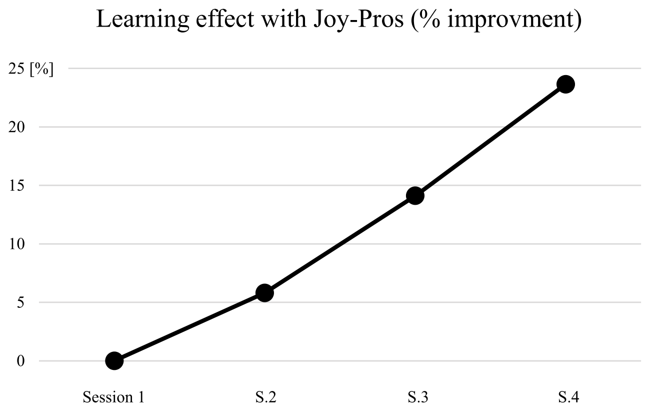


FIGURE 7. The learning effect during the four sessions conducted with the end user: percentage improvement is calculated in reference to the first session considering its value as 100%.

selected for this task was Minecraft because of its simplicity and familiarity. The task assigned to the participants was to build a simple house similar to one that was shown to them in a photo. The participants were asked just to follow the general structure of the house, and not to necessarily adhere to the details. After the task was finished the participants were asked to answer a questionnaire regarding their experience using the Joy-Pros to measure their satisfaction with the controller's performance and form-factor and their subjective evaluation of the physical and mental effort required to use it. The questions were adopted from the work of Douglas, Kirkpatrick, and MacKenzie [8]. The questionnaire items and the participants' responses are shown in figure 9. All the participants finished the task within 30 minutes.

VI. DISCUSSIONS

A. THROUGHPUT

The results of the throughput experiment showed the Joy-Pros to be slightly outperforming the thumbstick of a game controller (XBox one controller) in terms of throughput and movement time when used by the intact participants. This result is consistent with the rationale behind the design of Joy-Pros, which was based on the findings of Balakrishnan and MacKenzie [13]; the forearm outperforms the fingers as a pointing device.

With the end user, the throughput result was similar in the first session, and the throughput value was consecutively higher with the following sessions. The four sessions were spaced two weeks apart, and the end user used Joy-Pros only during the experiment time. The learning effect curve during the four sessions (figure 7) shows a 23% improvement in throughput in the last session compared to the first session. These results are very promising for the use of Joy-Pros by persons with upper limb deficiencies, since they show the ability to achieve similar control level to the gaming controller, and the prospect of improving their control performance overtime and with practice. Similar learning effect measurements were not conducted in this research for the other input devices since these devices enjoy a high familiarity factor, however, such measurements will be needed in the next experiment to further investigate the learning effect of the different input devices.

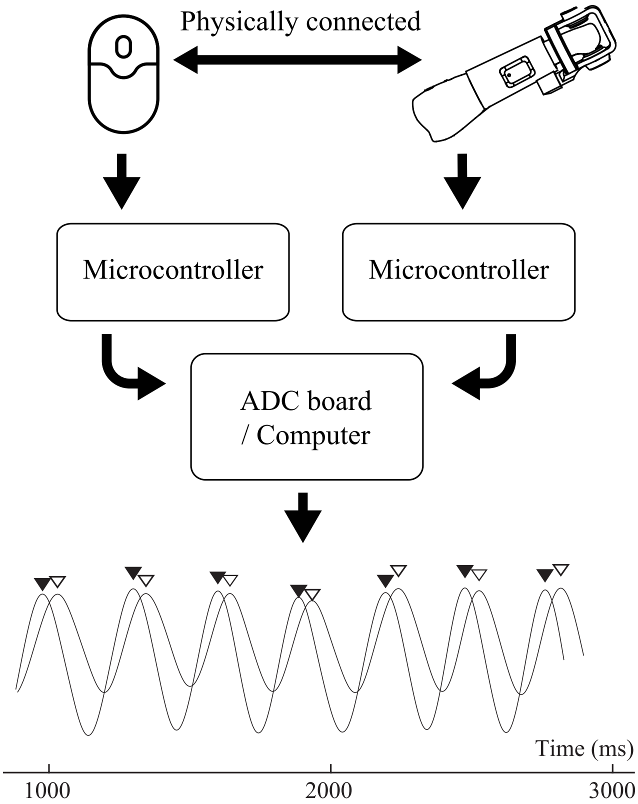


FIGURE 8. Illustration of the system setup for measuring relative latency difference between a PC gaming mouse and the Joy-Pros.

The computer mouse, expectedly, outperformed the Joy-Pros and the XBox controller. This is consistent with previous researches that have found the mouse to outperform other pointing devices with varying margins [6], [8]. The computer mouse uses the synergy of the shoulder, elbow, wrist, and fingers, and enjoys a very high familiarity factor. The mouse also has an advantage in traction on the mouse pad. Understanding the factors that result in the superior performance of the mouse is beyond the scope of this work. However, using the mouse as the golden standard and comparing the performance of other game controllers to a PC mouse helps make a judgment on the controller performance, and what types of games or class of para-esports the controller can be used for.

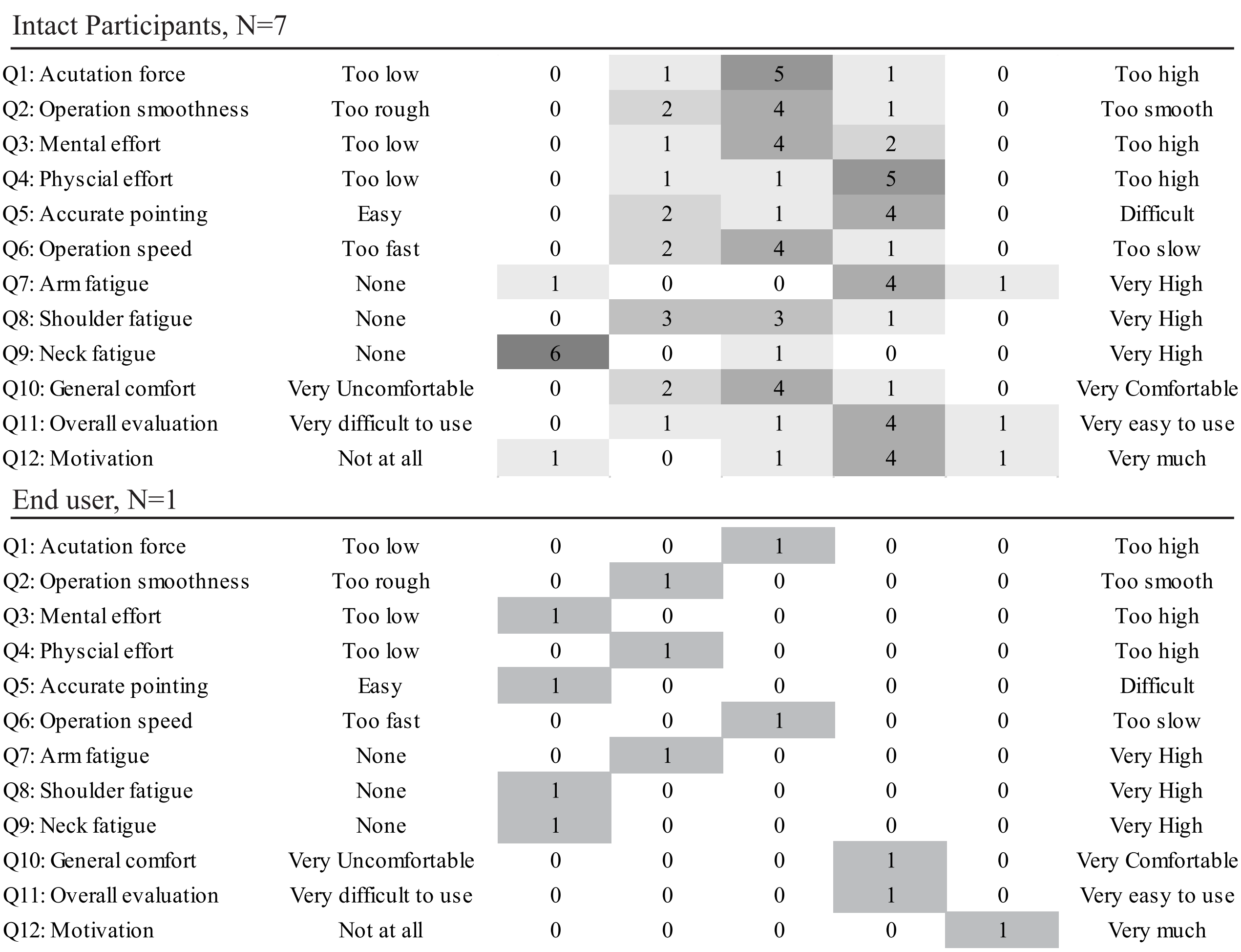
B. IN-GAME TASK/QUESTIONNAIRE

The in-game task experiment was designed to engage participants in a relatively longer gaming session with the Joy-Pros. The questionnaire provided insight into the participants' reception of the Joy-Pros 9. The results indicate that the physical effort (Q4) was relatively high, accurate pointing (Q5) was relatively difficult, and the arm fatigue (Q7) was relatively high. These results are likely due to the fact the participants had to suspend their right arm, using Joy-Pros, in the

TABLE 2. Evaluation questionnaire for in-game task experiment.

Please circle the x that is most appropriate as an answer to the given comment.

Q1. The force required for actuation was:	Too low - Too high
Q2. Smoothness during operation was:	Too rough - Too smooth
Q3. The mental effort required for operation was:	Too low Too high
Q4. The physical effort required for operation was:	Too low - Too high
Q5. Accurate pointing was:	Easy - Difficult
Q6. Operation speed was:	Too fast - Too slow
Q7. Arm fatigue was:	None - Very high
Q8. Shoulder fatigue was:	None - Very high
Q9. Neck fatigue was:	None - Very high
Q10. General comfort was:	Very uncomfortable - Very comfortable
Q11. Overall, the input method was:	Very difficult to use - Very easy to use
Q12. How motivated are you to use this controller in your gaming sessions:	Not at all - Very much



Intact Participants, N=7

Q1: Acutation force	Too low	0	1	5	1	0	Too high
Q2: Operation smoothness	Too rough	0	2	4	1	0	Too smooth
Q3: Mental effort	Too low	0	1	4	2	0	Too high
Q4: Physcial effort	Too low	0	1	1	5	0	Too high
Q5: Accurate pointing	Easy	0	2	1	4	0	Difficult
Q6: Operation speed	Too fast	0	2	4	1	0	Too slow
Q7: Arm fatigue	None	1	0	0	4	1	Very High
Q8: Shoulder fatigue	None	0	3	3	1	0	Very High
Q9: Neck fatigue	None	6	0	1	0	0	Very High
Q10: General comfort	Very Uncomfortable	0	2	4	1	0	Very Comfortable
Q11: Overall evaluation	Very difficult to use	0	1	1	4	1	Very easy to use
Q12: Motivation	Not at all	1	0	1	4	1	Very much

End user, N=1

Q1: Acutation force	Too low	0	0	1	0	0	Too high
Q2: Operation smoothness	Too rough	0	1	0	0	0	Too smooth
Q3: Mental effort	Too low	1	0	0	0	0	Too high
Q4: Physcial effort	Too low	0	1	0	0	0	Too high
Q5: Accurate pointing	Easy	1	0	0	0	0	Difficult
Q6: Operation speed	Too fast	0	0	1	0	0	Too slow
Q7: Arm fatigue	None	0	1	0	0	0	Very High
Q8: Shoulder fatigue	None	1	0	0	0	0	Very High
Q9: Neck fatigue	None	1	0	0	0	0	Very High
Q10: General comfort	Very Uncomfortable	0	0	0	1	0	Very Comfortable
Q11: Overall evaluation	Very difficult to use	0	0	0	1	0	Very easy to use
Q12: Motivation	Not at all	0	0	0	0	1	Very much

FIGURE 9. Responses of the in-game task experiment participants to the questionnaire.

air for the duration of the experiment; roughly 30 minutes each. This leads to high fatigue and physical effort and less accurate pointing. To address this issue Joy-Pros will have to be used with some sort of armrest that supports the elbow and allows for free movement of the forearm. This issue will be addressed in future research with a more elaborate investigation. Regardless to this issue, the questionnaire results showed relatively good overall evaluation of the Joy-Pros by the participants (Q11), and good motivation to use Joy-Pros in gaming sessions (Q12). The end user evaluation was more generous to the favor of Joy-Pros. This might be because of his interest in the device, or since he did not have a recent reference point of using a PC mouse similar to the intact participants.

C. LIMITATIONS

Due to the large individual differences between persons with upper limb deficiencies, experiments with multiple end users have to be conducted to verify the effectiveness of Joy-Pros with the target population. Persons with transradial amputation have limited ability to pronate or supinate the forearm based on the level of amputation. Joy-Pros theoretically avoids this problem by excluding the forearm pronation and supination in its sensing computation, but this issue should be verified experimentally in the future.

Besides pointing, two binary actions are assumed to be possible with Joy-Pros through the distal buttons (for persons with articulated wrist joints) or EMG sensors on the forearm, or through footswitches (for persons with transradial arm deficiencies). The distal buttons and the EMG activity might impose jitter on the pointing task, which might deteriorate the pointing accuracy or throughput depending on the amplitude of the imposed jitter. Jitter of small amplitudes was not found to significantly deteriorate the throughput in a pointing task in previous research [15], but it remains to be seen how much jitter will be generated with the used triggers and how it affects the pointing task. The frequency and accuracy by which these triggers can be activated also has to be investigated.

A common issue with MEMS-based gyroscopes is the eventual drift in their output. The chip used in Joy-Pros (BNO055) performs automatic background calibration of all sensors [29], but drifting was still observed during the use of Joy-Pros. Research on sensory fusion algorithms and drift compensation methods is needed to mitigate this issue.

VII. CONCLUSION

In this work we proposed design criteria for game controllers to enable para-esports based on the literature of information capacity of the human motor system, as in Fitts' law, and the concept of control dimensionality of video games and physical controllers. The prosthetic controller presented in this paper serves as one example of a controller designed with performance in mind. The experiments demonstrate the throughput achieved with the prosthetic controller (2.45 bit/s with intact users, 2.98 bps with an end user after 4 sessions) to be superior to a gaming console controller (2.19 bps with intact users). The learning effect with the prosthetic controller was shown to be 23% in the forth session, which indicates a headroom for performance improvement. Evaluation of the prosthetic controller by the experiment participants showed additional physical burden when controlling the game using the forearm, which should be addressed in future works through improvements to the ergonomics of the device, and through the use of elbow support methods. However, 5 out of the 7 participants where in favor of using the controller. Sensor fusion methods should also be investigated to mitigate the sensor drift issue introduced by the inertial measurement unit. Similar to para-sports, para-esports will need to be organized in classes that consider the game type and the type of physical disability of the athletes, and each class will require a controller suitable for its content and participants.

ACKNOWLEDGMENT

The authors would like to express their gratitude to the experiments' participants for their valuable contribution and feedback on this work.

REFERENCES

[1] R. Rietkerk. *Newzoo: The Global Esports Audience Will Be Just Shy of 500 Million This Year*. Accessed: Feb. 12, 2022. [Online]. Available: https://newzoo.com/insights/articles/newzoo-esports-sponsorship-alone-w%ill-generate-revenues-of-more-than-600-million-this-year/

[2] K. Amazan-Hall, J. J. Chen, K. Chiang, A. L. L. Cullen, M. Deppe, E. Dormitorio, D. Haynes, J. Kernan, K. Quanbeck, M. Romine, B. Ruberg, J. Song, J. Stepan-Norris, C. Steinkuehler, and A. Trammell, "Diversity and inclusion in esports programs in higher education: Leading by example at UCI," *Int. J. Gaming Comput.-Mediated Simul.*, vol. 10, no. 2, pp. 71–80, Apr. 2018.

[3] F. Cordella, A. L. Ciancio, R. Sacchetti, A. Davalli, A. G. Cutti, E. Guglielmelli, and L. Zollo, "Literature review on needs of upper limb prosthesis users," *Frontiers Neurosci.*, vol. 10, p. 209, May 2016.

[4] D. Gadia, M. Granato, D. Maggiorini, M. Marras, and L. A. Ripamonti, "A touch-based configurable gamepad for gamers with physical disabilities," in *Proc. Int. Conf. Comput.-Hum. Interact. Res. Appl. (CHIRA)*. Setúbal, Portugal: SciTePress, INSTICC, 2017, pp. 67–74, doi: 10.5220/0006508800670074.

[5] F. Iacopetti, L. Fanucci, R. Roncella, D. Giusti, and A. Scebba, "Game console controller interface for people with disability," in *Proc. Int. Conf. Complex, Intell. Softw. Intensive Syst.*, 2008, pp. 757–762.

[6] A. Zaranek, B. Ramoul, H. F. Yu, Y. Yao, and R. J. Teather, "Performance of modern gaming input devices in first-person shooter target acquisition," in *Proc. CHI Extended Abstr. Hum. Factors Comput. Syst.*, 2014, pp. 1495–1500.

[7] P. M. Fitts, "The information capacity of the human motor system in controlling the amplitude of movement," *J. Experim. Psychol.*, vol. 47, no. 6, p. 381, 1954.

[8] S. Douglas, A. Kirkpatrick, and I. MacKenzie, "Testing pointing device performance and user assessment with the ISO 9241—Part 9 standard," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, Jan. 1999, pp. 215–222.

[9] R. W. Soukoreff and I. S. MacKenzie, "Towards a standard for pointing device evaluation, perspectives on 27 years of Fitts' law research in HCI," *Int. J. Hum.-Comput. Stud.*, vol. 61, no. 6, pp. 751–789, Dec. 2004.

[10] D. M. Pham and W. Stuerzlinger, "Is the pen mightier than the controller? A comparison of input devices for selection in virtual and augmented reality," in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, Nov. 2019, pp. 1–11.

[11] G. Young, A. Kehoe, and D. Murphy, *Usability Testing of Video Game Controllers: A Case Study*. New York, NY, USA: Association for Computing Machinery, May 2016, pp. 145–188.

[12] D. Natapov, S. J. Castellucci, and I. S. MacKenzie, "ISO 9241–9 evaluation of video game controllers," in *Proc. Graph. Interface (GI)*, 2009, pp. 223–230.

[13] R. Balakrishnan and I. S. MacKenzie, "Performance differences in the fingers, wrist, and forearm in computer input control," in *Proc. ACM SIGCHI Conf. Hum. Factors Comput. Syst.*, Mar. 1997, pp. 303–310.

[14] H.-J. Chen, C. J. Lin, and P.-H. Lin, "Effects of control-display gain and postural control method on distal pointing performance," *Int. J. Ind. Ergonom.*, vol. 72, pp. 45–53, Jul. 2019.

[15] R. J. Teather, A. Pavlovych, W. Stuerzlinger, and I. S. MacKenzie, "Effects of tracking technology, latency, and spatial jitter on object movement," in *Proc. IEEE Symp. 3D User Interface*, 2009, pp. 43–50.

[16] Y. Garrido, L. Marco, J. Segura, T. Blanco, and R. Casas, *Accessible Gaming through Mainstreaming Kinetic Controller*, vol. 9. Berlin, Germany: Springer, Jun. 2009, pp. 68–77.

[17] N. Villar, K. M. Gilleade, D. Ramdunyellis, and H. Gellersen, "The VoodooIO gaming kit: A real-time adaptable gaming controller," *Comput. Entertainment*, vol. 5, no. 3, p. 7, Jul. 2007.

[18] S. Stark and C. Sarkar. (May 2018). *Microsoft's New Xbox Controller is Designed Entirely for Players With Disabilities*. [Online]. Available: https://www.polygon.com/2018/5/17/17363528/xbox-adaptive-controller-dis%ability-accessible

[19] D. Maggiorini, M. Granato, L. A. Ripamonti, M. Marras, and D. Gadia, "Evolution of game controllers: Toward the support of gamers with physical disabilities," in *Computer-Human Interaction Research and Applications*, A. Holzinger, H. P. Silva, and M. Helfert, Eds. Cham, Switzerland: Springer, 2019, pp. 66–89.

[20] D. Bednárek, M. Kruliš, J. Yaghob, and F. Zavoral, *Player Performance Evaluation in Team-Based First-Person Shooter eSport*. Cham, Switzerland: Springer, 2018, pp. 154–175.

[21] M. Schubert, A. Drachen, and T. Mahlmann, "Esports analytics through encounter detection," in *Proc. MIT Sloan Sports Anal. Conf.*, Cambridge, CA, USA: MIT Sloan, 2016, pp. 1–18. [Online]. Available: https://portal.research.lu.se/en/publications/esports-analytics-through-encounter-detection

[22] V. Lipovaya, Y. Lima, P. Grillo, C. E. Barbosa, J. Souza, and F. Duarte, "Coordination, communication, and competition in esports: A comparative analysis of teams in two action games," in *ECSCW Exploratory Papers*. Nancy, France: European Society for Socially Embedded Technologies, Jun. 2018.

[23] M. H. Rezvani and D. Khabiri, "Gamers' behaviour and communication analysis in massively multiplayer online games: A survey," in *Proc. 2nd Nat. 1st Int. Digit. Games Res. Conf., Trends, Technol., Appl. (DGRC)*, Nov. 2018, pp. 61–69.

[24] N. Khromov, A. Korotin, A. Lange, A. Stepanov, E. Burnaev, and A. Somov, "Esports athletes and players: A comparative study," *IEEE Pervasive Comput.*, vol. 18, no. 3, pp. 31–39, Jul. 2019.

[25] C. Bateman and R. Boon, *21st Century Game Design (Game Development Series)*. Newton, MA, USA: Charles River Media, 2005.

[26] M. M. Mustaquim and T. Nyström, "Video game control dimensionality analysis," in *Proc. Conf. Interact. Entertainment*, Dec. 2014, pp. 1–8.

[27] T. Inc. *Trs Socket Simulator Pro Cuff*. Accessed: Feb. 12, 2022. [Online]. Available: https://www.trsprosthetics.com/product/pro-cuff/

[28] S. MacKenzie. *Fitts' Law Software*. Accessed: Feb. 12, 2022. [Online]. Available: http://www.yorku.ca/mack/FittsLawSoftware/

[29] *Bosch Sensortec. Bno055 Datasheet*. Accessed: Feb. 12, 2022. [Online]. Available: https://www.bosch-sensortec.com/media/boschsensortec/downloads/datashee%ts/bst-bno055-ds000.pdf

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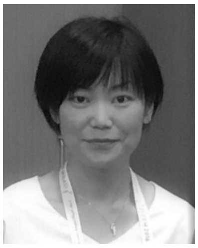

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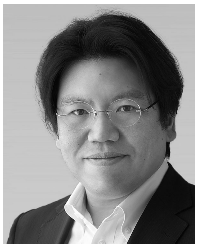

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