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Article

Virtual Gymnasium: Personalized Weight Perception Interface in Lifting Virtual Objects

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Abstract: This paper proposes a pseudo-haptic interface that depicts the virtual weights of dumbbells in a virtual gymnasium. When a user performs a dumbbell biceps curl, he/she fixes the elbow joint as a standard joint and lifts the dumbbell, with its movement trajectory represented as a circular arc. The trajectories and velocity of dumbbell bicep curls differ depending on human physiological characteristics. Therefore, the proposed system provides an adaptable exercise area and force visualization of virtual dumbbells using a velocity-based pseudo-haptic interface and computer vision-based tracking method. The system recognizes the position and rotation of joints related to a dumbbell biceps curl with the implementation of density-based spatial clustering of applications with noise (a clustering algorithm) and resizes the radius and angle of an integrated force circular gauge. Furthermore, when a user lifts a dumbbell, the system recognizes, using linear regression, the current position and lifting force of the virtual dumbbell and visualizes the current lifting force with a guided movement trajectory to match the lifting force. Experimental results show that the proposed pseudo-haptic interface increased weight perception and usability by up to 30% compared to conventional methods ($p < 0.05$).

Keywords: pseudo-haptic interface; weight perception; virtual fitness; virtual reality; augmented virtuality

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1. Introduction

The immersive technology of augmented virtuality (AV) is widely used in many applications related to serious games, such as sports, healthcare, and rehabilitation [1–6]. To add real-world information to the virtual world, the process of serious games can consist of three fields: recognition, calculation, and representation [7,8]. Recognition in terms of human body information tracks (or identifies and classifies) the joints of the human body, in what is called the human pose estimation method, using computer vision-based technology [9]. Although recent human pose estimation methods provide high accuracy using deep learning-based algorithms, they are difficult to apply to augmented virtuality serious games because of performance issues. Hence, augmented virtuality serious games generally use conventional computer vision tracking methods [6] or controllers for performance. A serious game calculates the state based on recognized information and delivers results of the recognition to a user in the representation process. In the representation process, it is necessary to provide various perception methods to achieve the goal of augmented virtuality.

In this study, we focus on the representation of virtual object manipulation using a human body tracking method, which is one of the challenging issues in augmented virtuality serious games. A user can grasp a virtual object and manipulate it with his/her real hands using a human body tracking method. Virtual perception of a virtual object is essential for perceiving the weights of virtual objects to increase the sense of presence and virtual experience in augmented virtuality serious games, such as sports and health care.

Several researchers have focused on simulating mass in virtual objects by using haptic and visual senses. To obtain the sensation of mass in VR through haptic senses, exoskeleton-based haptic feedback interfaces have been used, where the devices are attached to body parts to provide forces on different parts of the body [10,11]. Although haptic devices provide accurate and direct weight perception, they are generally expensive and difficult to wear and use in augmented virtuality serious games. Alternatively, a pseudo-haptic feedback approach has been used to simulate virtual weights to reduce the complexity of the haptic device. To provide weight perception of virtual objects with pseudo-haptic feedback, visualization of different heaviness of virtual objects is combined with simplified device feedback, such as tactile, skin pressure, and vibration [7,12–15]. Although pseudo-haptic feedback has established the feasibility of weight perception of virtual objects without complex haptic devices, the user still wears or carries some devices. Furthermore, conventional research restricts possible weight perception areas to the human hand. It is difficult to extend to other areas of the human body because of limited device configurations.

Because of the above, recent virtual object weight perception research has focused on extending the perception area from the hand to the human body [16–18]. According to the experimental results, specific body postures and gestures can increase weight perception in terms of lifting objects. Another pseudo-weight perception method, which controls the lifting force of virtual objects with visual feedback, showed enhanced results of weight perception [16,19,20]. Although conventional weight perception methods improve the representation of virtual weights, the effect of weight perception is less effective for people with different body sizes, because the conventional weight perception module is mostly designed with a bias toward the median adult male body size. Furthermore, the material-weight illusion (MWI) issue can be raised by differences in the visual appearances of virtual objects of the same mass [21–24]. Users may feel lighter when they lift a heavier-looking object and heavier when they lift a lighter-looking object.

Here, we proposed a personalized weight perception interface based on the physical characteristics of users when lifting virtual objects.

Toward this, a virtual gymnasium (VG) was created to provide the opportunity for gymnasium (gym) exercises using the proposed pseudo-weight perception method. The salient feature of this system is that it provides a personalized weight perception interface by controlling the lifting force and customizing visual feedback according to the individual user body size. The proposed VG method creates a visualization of a circular (green to red) bar to represent the difference between the standard force required to lift a virtual dumbbell and the current force applied by the user. When the user lifts a virtual dumbbell in any exercise scenario, the circular bar indicates the difference between applied and actual forces using a machine learning algorithm. The user must place the circular bar in the middle to obtain the sensation of the actual weight. Hence, the proposed method visualizes a circular arc interface to guide the movement trajectory of every lifting process. The position and size of the circular arc interface can be changed according to the body size of each user.

The main contributions of this study are as follows:

- The proposed system provides a novel, personalized virtual weight perception interface that allows users to perceive the optimized weights of virtual objects during the lifting process by recognizing the user's upper body size.
- The system provides both one-handed and two-handed lifting algorithms to support various lifting exercises, such as dumbbell and barbell curls.

2. Related Work

2.1. Augmented Virtuality Serious Game

VR technology gives users the impression of walking among computer graphics and operating objects within the virtual environment. VR is generally used in a variety of environments and applications, and it has been classified along a reality-virtuality continuum [3], as shown in Figure 1, according to the display environment and degree of representation of virtual objects.

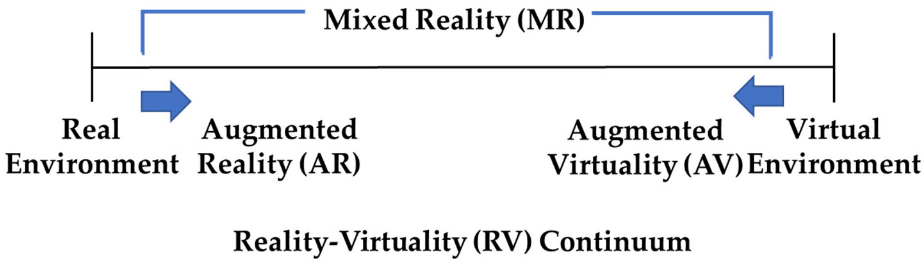

Figure 1. Milgram's reality-virtuality continuum [3].

The real environment refers to the real world, and the virtual environment is a world in which everything is expressed in 3D VR. Augmented reality is the integration of virtual representations with the real environment. Augmented virtuality implies that a real environment, which includes a user, can be projected onto a virtual environment. Because augmented virtuality allows a user to recognize information from the real world in VR, it has been widely used in the field of serious games, where information between the real environment and the virtual environment are closely linked. Lin et al. [4] developed a stroke rehabilitation serious game, which records the best performance for each patient and adapts gameplay. Almousa et al. proposed an augmented virtuality serious game for the upper limb stroke rehabilitation process [5]. Lee et al. proposed a VG to increase exercise effects by lifting a dumbbell [6]. Although the purposes of the games are different, they use characteristics similar to augmented virtuality, which is virtual object manipulation with the user's hands.

2.2. Weight Perception

The immersion in virtual environments challenges researchers to provide real grasping and sensation during virtual object manipulation. Many systems have been developed for manipulating virtual objects in VR, but the technologies used in these systems are differ from each other. The concern of every system is the method of grasping and interacting with virtual objects to recognize the appropriate feedback in VR.

Ott et al. proposed an integration of three different haptic devices for the generation of realistic haptic feedback on virtual object manipulation [10]. With the integration of haptic devices, they proposed various haptic feedback for virtual objects, such as force feedback through haptic arms and hands. Borst et al. proposed the virtual grabbing and manipulation of objects using a magnetic data glove consisting of haptic devices. They developed linear and torsional spring-damper models with articulated hand models to accurately track 3D hand information for grasping virtual objects [11]. Although the proposed models showed good experimental results in terms of perceiving the direct weights of virtual objects using force feedback, usability issues emerged because of the complexity of the haptic devices.

Lecuyer et al. discovered that visual feedback can replace haptic feedback, which is also known as "pseudo-haptic feedback." Pseudo-haptic feedback can easily be extended to simple haptic feedback, such as tactile and vibration [12]. To understand the concept underlying weight perception research, it has been applied to visualize various feedback of object grasping with the simulation of various simple haptic elements, such as stiffness, distance, visual appearance, or lifting force of a virtual object. Hummel et al. proposed a pseudo-weight perception method using a wireless finger-tracking device when a user grabs and manipulates a virtual object [13]. Pseudo-haptic feedback was adaptively generated based on the distance between the thumb and index fingers used to grab the virtual object. Giachritsis et al. developed a multi-finger haptic interface for pseudo-weight perception methods in unimanual and bimanual lifting tasks [14]. Minamizawa et al. proposed a wearable haptic device known as a gravity grabber, which is attached to the index finger and thumb to present weight sensations in virtual objects [15]. The user can feel the augmented weight and inertia of the virtual object while holding an empty glass and feels the weight of water that is virtually poured into it. Although the results of the experiments showed the possibility of a combination of visual and simple haptic feedback, the weight perception area is restricted to only the fingers.

Another weight perception research focused on the extension of the perception area from hand to arm. Hanning et al. developed a pneumatic pseudo-haptic device to represent the weight perception of virtual objects. Because the pneumatic pseudo-haptic device can alter the air pressure levels of the haptic interface surrounding a user's arm, various weights can be perceived according to different air pressure levels [16]. Zenner et al. investigated dynamic passive haptic feedback for weight perception [17]. They proposed a combination of active haptic feedback with actuators and visual passive feedback, called a physical proxy, to represent the weights of virtual objects. The results showed that the potential combination and adaptation of feedback could enhance weight perception. Achibet et al. proposed a body-mounted elastic armature to improve interaction by providing passive haptic feedback to the user's hand [18]. The proposed elastic armature links the user's hand to his/her body and processes an egocentric force when extending the arm. An elastic armature was applied for object manipulation and weightlifting. Although the proposed research showed enhanced results in terms of weight perception, a user still wears or holds a specific device to perceive the weights of virtual objects.

Research on weight perception without wearing or attaching cumbersome haptic devices has focused on changing colors or indicators to provide an appropriate weight perception of virtual objects. Ban et al. conducted a psychological study exposing how weight perception while grasping objects is affected by visual perception. Based on this knowledge, they developed a visual feedback system that changes the brightness of virtual objects to control weight perception and fatigue [19]. After detecting the area of an object, the system changes its saturation and brightness values through its weight perception algorithms. Lee et al. presented a visual pseudo-weight perception method by controlling the current lifting force of virtual objects without attaching haptic devices [20]. They used a computer vision-based tracking system to recognize hand motions, such as grasping, releasing, and lifting. With the calculation of the gap between the current lifting and ideal lifting forces, their system provided a "force arrow" interface to indicate the force gap and provide weight perception. Although conventional weight perception methods improved the representation of virtual weights, they are not adapted to a user's personal characteristics.

Another consideration of the pseudo haptic interface is to overcome the material-weight illusion (MWI) issue. When users are lifting objects of same size, participants perceive lighter even though the visual appearance is heavier-looking [21–24]. Because MWI is affected by visual appearance, stimulating other properties in terms of visual feedback and sensations of a pseudo haptic interface is important to provide proper weight perception when lifting a virtual object.

Hence, personalization and adaptation may increase the sense of presence in VR applications. Mourtzis et al. proposed a personalized perception method that adapts educational content to students' profiles for factory education in an extended reality environment [25]. Although the domains are different, the idea of personalization can be applied to weight perception of lifting virtual objects.

3. Research Question

To address some of the above-mentioned gaps and challenges, we wanted to investigate if weight perception could be enhanced by a personalized interface adaptable to the body size of a user, which guides both lifting force and lifting movement along a personalized movement trajectory. We also asked about the difference between the exercising effects of lifting a virtual object along a personalized movement trajectory from those of conventional virtual weight perception methods. Furthermore, we were interested in how different weights could be perceived when the exercise process lifts an object with only one hand, when an object is lifted with both hands, and when a two-handed object, such as a barbell, is lifted. We intend to determine the relationship between these differences and the lifting force control through personalized weight perception. Therefore, we designed two user studies. First, we compared the proposed personalized weight perception method with conventional weight perception methods. Second, we developed and compared three contents of lifting exercises.

4. Force Gauge Circular Graphical User Interface

4.1. System Overview

The implementation of the proposed pseudo-weight perception method is described using system diagrams. Figure 2 illustrates the architecture of the proposed system. The human tracking system Kinect V2 tracks the 3D positions and movements of the left and right hands, elbows, and shoulders for data input through the input manager. The system calculates the average distance between joints in the calibration process. Then, the personalized movement trajectory is generated using the data and Equations (1) and (2). After calibration, the obtained data were integrated into the weight perception manager. The system checks the interaction between the user and virtual dumbbell using the Kinect device.

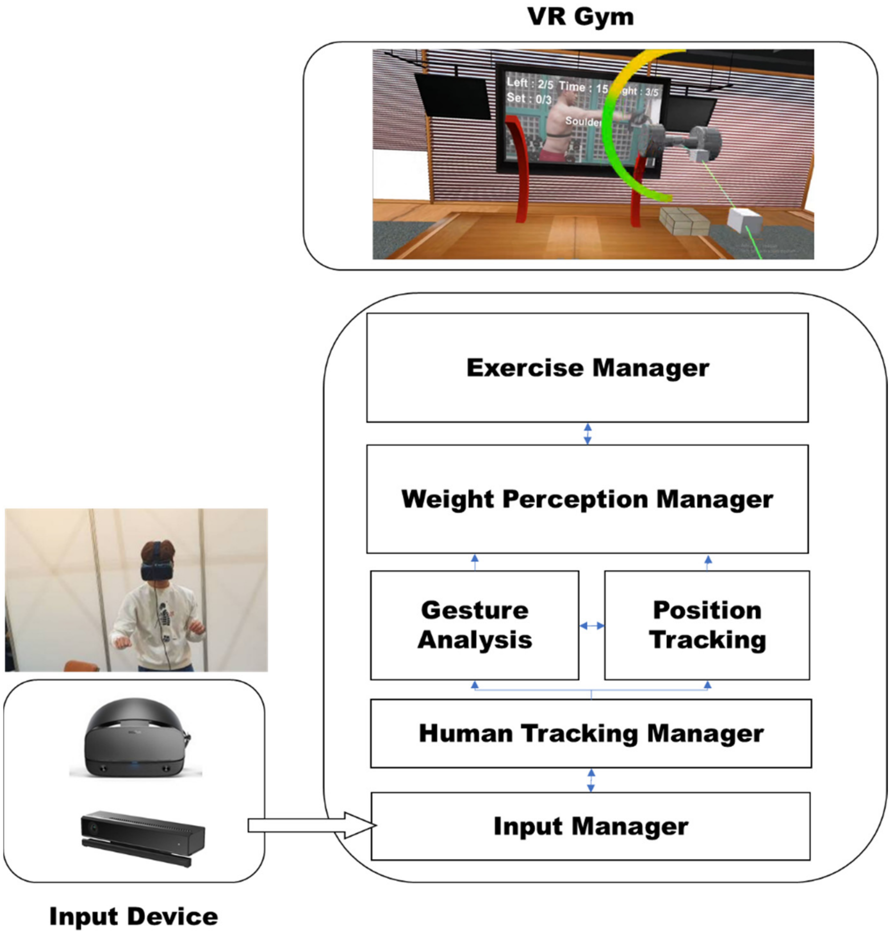

Figure 2. System architecture.

When grasping occurs, collision detection is performed between the user's hands and virtual dumbbell. After confirming grasping occurrence, the pseudo-weight perception algorithm executes and attains the current lifting forces by calculating the current lifting force, as defined in Equation (8).

This paper proposes a force gauge circular graphical user interface (FGCGUI) that allows users perceive personalized weight by controlling the lifting force of a virtual object. When a user grasps the virtual dumbbell at point A (Figure 3) and moves toward point B, the proposed algorithm begins to store the hand's position at every point between points A and B. During the lifting process, the user selects a standard joint such as the elbow, as shown in Figure 3. Thus, the movement trajectory of a dumbbell is generally represented as a circular arc according to the length of the user's arm. Another consideration is that the lifting force generally changes according to the differences in the weight of virtual objects during the exercise process. If an appropriate lifting force for the virtual object and an appropriate lifting movement guideline are provided, users can feel an appropriate sense of weight when lifting the virtual object.

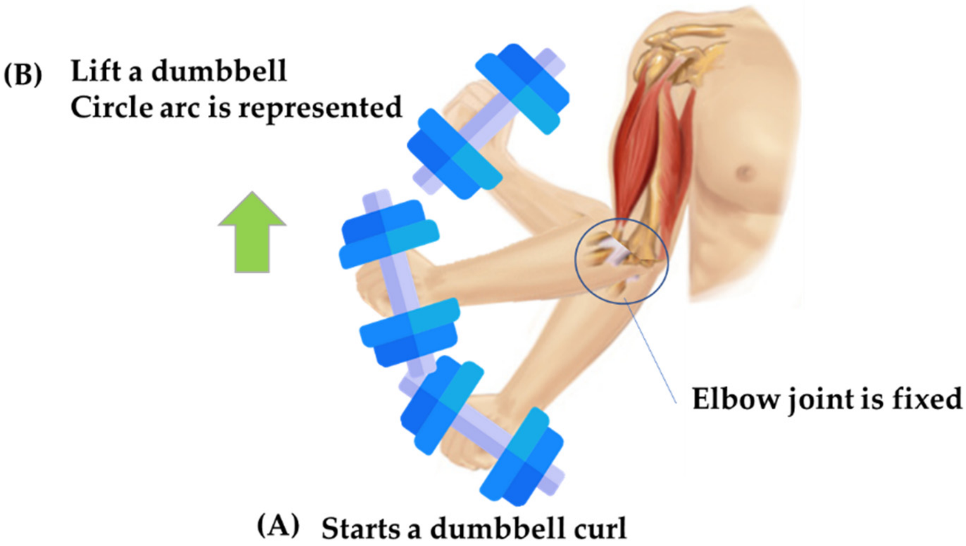

Figure 3. Exercise process. (**A**) Starts current dumbbell curl where the elbow joint is fixed as a standard joint. (**B**) A user lifts a dumbbell, and the movement trajectory is represented as a circular arc.

4.2. Movement Trajectory

The proposed FGCGUI also visualizes the movement trajectory to provide proper weight perception and exercise effects (Figure 4). Because the lifting curl is a repetitive exercise that visualizes a circular arc using an elbow joint fixed as a standard joint, the proposed system generates a customized movement trajectory according to sampled data with the density-based spatial clustering of applications with noise (DBSCAN) clustering algorithm, based on the length of the arm of the user [26]. The proposed system samples the positions of the hands while the user lifts a virtual object and creates a customized movement trajectory based on the sampled positions. However, the sampled positions may not be accurate owing to recognition errors and changes in each input. The proposed system generates a movement trajectory as non-uniform rational B-spline (NURBS) curves using De Boor's algorithm [27] (Figure 4). If the sampled positions are d_i, then the total number of sampled positions can be set to n, sampled points (de Boor points) are p_i, knots which produce a vector that defines the domain of the curve can be set to u_j, B-splines function of degree n is set to $N_i^n(u)$ as described in Equation (1). Linear interpolation can be performed sequentially on d_i n times for each section between the positions. Because the linearly interpolated values should be calculated using the curved movement trajectory, we calculated them as a B-spline curve in a 3D space. The result of this calculation is the sum of the B-spline functions, as described in Equation (2). Figure 4 shows the generation of the movement trajectory of the curve using De Boor's algorithm when there are four sampled positions from p0 to p3, the outermost lines connecting them linearly, and their knots being from u = 0 to u = 3. Because the sampled positions become the outermost line and the curve is created accordingly, the proposed system determines the sampled positions located at the outermost part of the recognized hand of the user.

$$\begin{gathered} r(u) = p_0N_0^3(u) + p_1N_1^3(u) + p_2N_2^3(u) + \cdots + p_nN_n^3(u) \\ r(u)\text{ is the function of B-spline curve with a given knots} \\ p_i : \text{sampled points(de Boor Points)},\ i = 0,\ 1,\ \ldots,\ D-1 \\ N_i^n(u)\ : \text{B-splines basic function of degree } n(=3) \\ u_j : \text{knots produce a vector that defines the domain of the curve,} \\ j = 0,\ 1,\ \ldots,\ K-1,\ \text{where } K = D+n+1 \end{gathered} \tag{1}$$

$$\begin{gathered} N_i^n(u) = \frac{u-u_{i-1}}{u_{i+n-1}-u_{i-1}}N_i^{n-1}(u) + \frac{u_{i+n}-u}{u_{i+n}-u_i}N_{i+1}^{n-1}(u) \\ N_i^0(u) = \begin{cases} 1 \text{ if } u_{i-1} \le u \le u_i \\ \text{o else} \end{cases},\ \sum_{i=0}^{D-1} N_i^n(u) = 1 \end{gathered} \tag{2}$$

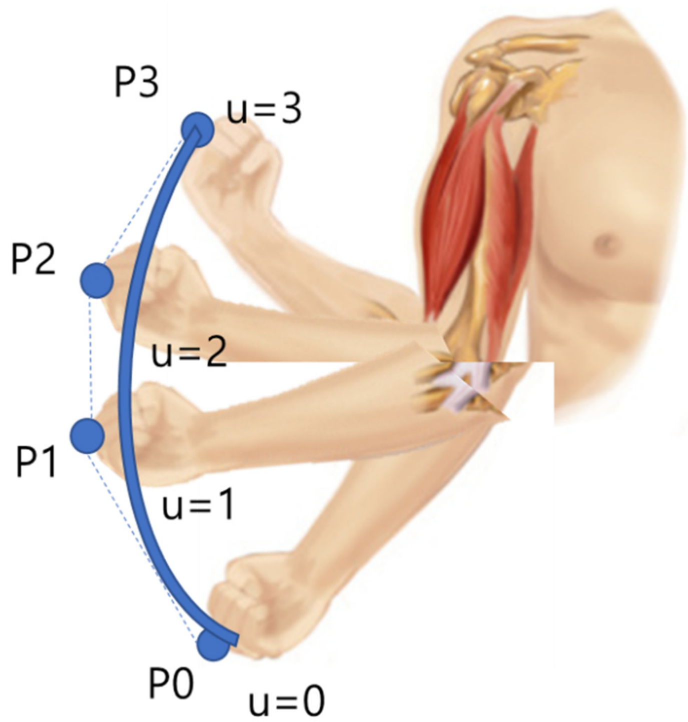

Figure 4. Example of the generation of movement trajectory.

Figure 5 shows the movement trajectory created using Equations (1) and (2) in a VR environment. When a user creates a movement trajectory, he/she repeats the lifting process following a video of the fitness trainer's exercise process (Figure 5). The proposed system then creates a personalized movement trajectory using the sampled positions of the elbow and hand of the user. The movement trajectory also changes depending on the exercise type.

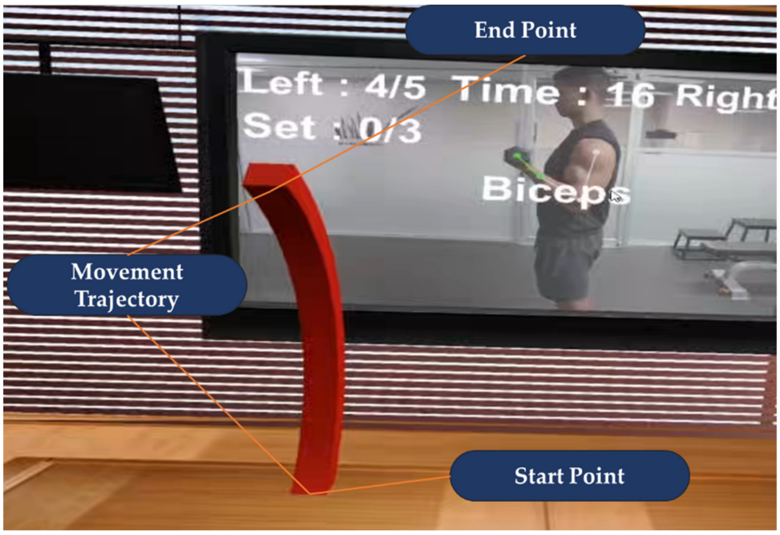

Figure 5. Customized movement trajectory in terms of a dumbbell curl process.

4.3. Controlling Lifting Force

Throughout the weight-lifting process, the FGCGUI shows whether the current applied force exceeds or does not exceed the standard force according to the given virtual dumbbell's weight and allows the user to control the force according to the FGCGUI. When the user grasps a virtual dumbbell, the proposed algorithm obtains information about the position and rotation of the hands, elbows, and arms through the Kinect sensor. The velocity can be found with distance d at point A at time t_2 and distance d at point B at time t_1 using Equation (3).

$$V_{user} = \Delta\text{hand position}/\Delta\text{time}. \quad (3)$$

After grasping the virtual dumbbell, the FGCGUI system stores all the values at each point between points A and B. Hence, every point becomes a new point and has a velocity value. Velocity regulates the magnitude of the lifting force. Nevertheless, the FGCGUI system depends on the force. Thus, acceleration is required, and the variation in velocity seems to be proportional to the lifting forces. However, the FGCGUI system considers the forces required to lift a real dumbbell's weights. According to the given velocity at all points between points A and B, the acceleration can be obtained using Equation (4).

$$A_{user} = \Delta V_{user}/\Delta\text{time}. \quad (4)$$

After obtaining the acceleration from the user, FGCGUI requires force from the user. The proposed system should calculate a virtual force to lift the virtual object. However, because there is no experimentally resolved guideline for the relationship between the virtual force for lifting a virtual object and the force for lifting a real object, we decided to use the same virtual force as the force for lifting a real object. Thus, according to Newton's second law, the acceleration of an object is reliant on a dual variable: the interim net force upon the object and the mass of the object. As the mass of an object increases, its acceleration decreases. Thus, the user force can be calculated using Equation (5).

$$F_{user} = M_{virtual\ dumbbell\ weight} \times A_{user}. \quad (5)$$

The proposed system calculates the shape and length of the FGCGUI based on the two forces. The first force is the user input force while perceiving a virtual weight, and the second force is the guided force, which demonstrates and evaluates the applied user force while lifting a virtual weight. The user force F_{user} is based on the user acceleration A_{user}. Similarly, the guided force F_{guided} is based on the guided acceleration A_{guided}: The procedure for obtaining the $_{user}$ is based on the runtime while picking the virtual weight.

The FGCGUI system is based on three types of exercises in which the user can perceive weight. Thus, A_{guided} is influenced by the type of exercise, weight of the dumbbells, and the angle of rotation of the arms. Acceleration was obtained within a very short interval. Therefore, the length of the area is not required.

The Kinect sensor was used to obtain rotation data from the user for A_{guided} because of the Kinect sensor limitation, and the data were noisy. Often, the speed and acceleration of the hands suddenly change drastically, even if you keep your hand still. It appropriately interpolates the values of the current acceleration and previous acceleration to compensate for this. Because the cycle of obtaining the acceleration is very short, it does not give a feeling that the acceleration changes slowly owing to interpolation. After obtaining the data from Kinect, they were scanned using DBSCAN. After completing the scanning process, the scanned data were subjected to linear regression, and the guided acceleration was obtained using Equation (6).

$$A_{guided} = \text{Linear Regression} \times \text{Real mass}/\text{Virtual mass} \tag{6}$$

The guided acceleration was obtained using linear regression. The guided force was obtained according to Newton's second law. Hence, F_{user} and F_{guided} are obtained. It can be stated that the force gage is the difference between guided and user acceleration.

As mentioned above, the acceleration of the hand has vividly changed and caused an interpolation between the current acceleration and previous point acceleration. Because the acceleration period is very short, there is no impression that the acceleration will slowly change owing to interpolation, but it affects the force. Equation (7) shows the final force after interpolation in terms of acceleration and speed. The F interpolation user was obtained by adding the same force to the user at two points.

$$F_{interpolarion\ user} = 0.4 \times F_{user-1} + \text{Real mass}/F_{user} \tag{7}$$

Because the FGCGUI system is based on force and a circular gage, it is important to note that the user interface (UI) is made using a unity circular scroll bar, and its value ranges from 0 to 1 (0.4–0.6 is the range of values between users). However, the exact force and perceived weight By the FGCGUI depends on the virtual mass, and the acting and guided forces change as the mass changes. Finally, a graphical UI was created, which represents the division between the exercising user and the system-guided forces to perceive the weight through visual feedback based on Equation (8).

$$\text{Result}_{UI} = \left(F_{interpolation\ user} \times 0.5\right)/F_{guided} \tag{8}$$

When a user grasps a weight, the circular gage instantiates in the head-mounted display (HMD). Initially, the gage is empty, but when the user applies the force to lift the weight, the circular gage starts filling from green to red. To provide an appropriate force to lift a virtual dumbbell, the proposed system is divided into three levels of current lifting force (Figure 6). If a user lifts the virtual dumbbell with a lack of force, FGCGUI visualizes the current lifting force in green, as shown in Figure 6A. If a user lifts the dumbbell with the proper force, FGCGUI visualizes the current lifting force in yellow, as shown in Figure 6B. If a user lifts the dumbbell with an excessive lift force, the FGCGUI visualizes the current lifting force in red, as shown in Figure 6C. Although we measured the guide force of real dumbbells with professional fitness trainers, the personal guide force of dumbbells can be changed differently according to personal characteristics [28,29]. To address this situation, the proposed system determines that the circular gauge varies between 0 and 1 as green and red, respectively, and the ideal point of the force gage is 0.4–0.6 when the user perceives the weight confidently, as described in Equation (8).

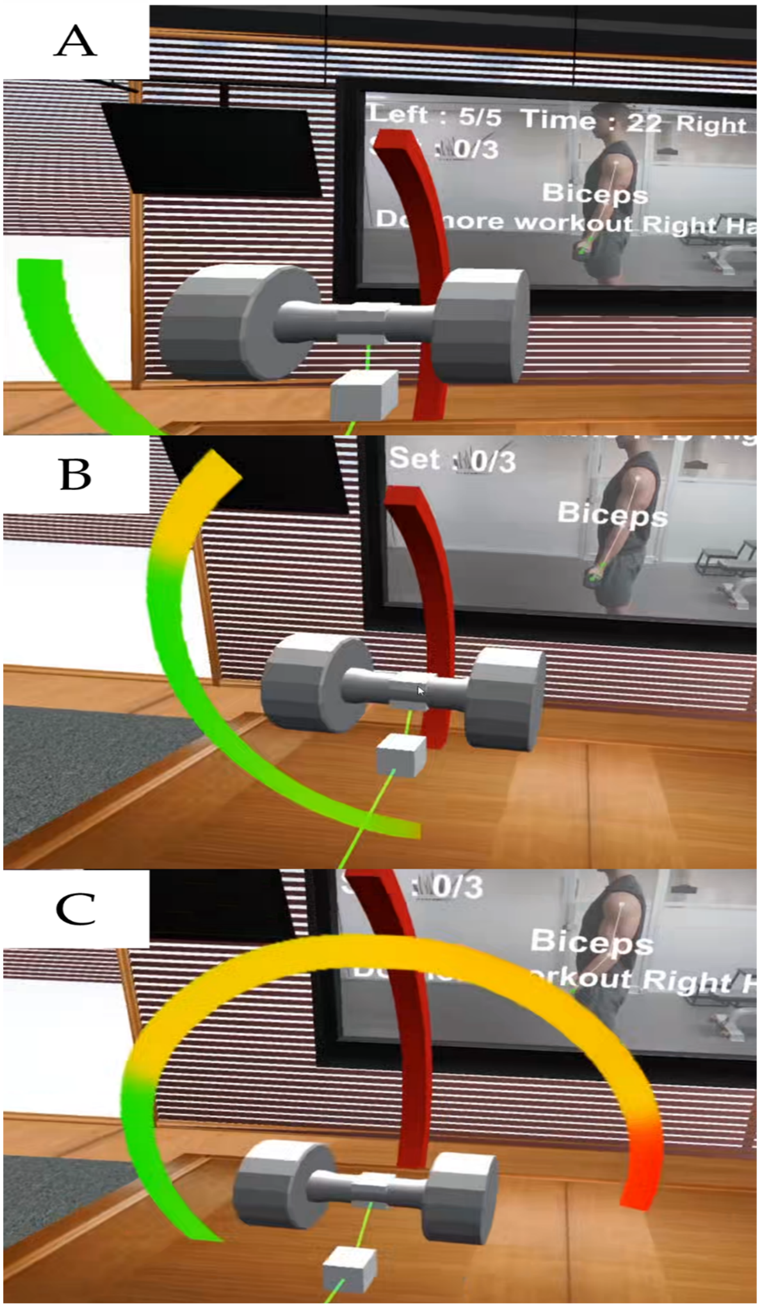

Figure 6. Force representations of FGCGUI: (**A**) lacking lift force, (**B**) proper lift force, and (**C**) excessive lift force.

4.4. Persoanlized Weight Perception Interface in Virtual Gymnasium

The FGCGUI was visualized as a combination of an arc-based movement trajectory and a circle-based force gauge (Figure 7). After adaptive generation according to the user's arm length, the arc-based movement trajectory is fixed during the lifting curl process. Nevertheless, the circle-based force gauge moved according to the current hand position during the lifting curl process.

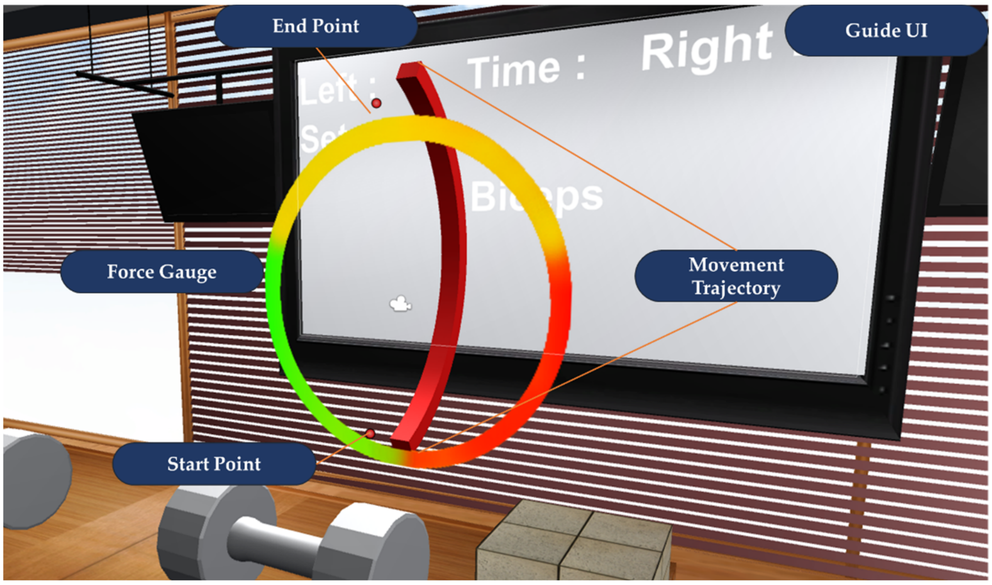

Figure 7. FGCGUI.

Figure 8 explains the overall process of the proposed personalized weight perception interface. When a user starts to calibrate the process, the proposed system measures the 3D position and distance of the left and right hands, elbow, and shoulder while the user stands in front of the Kinect sensor with changing upper body postures between t-pose and a-pose for 30 s. The proposed system samples specific 3D points of the exercise movements through the lifting behaviors of the user. Then, the proposed system generates the guided movement trajectory according to the sampling movements and 3D positions of the joints. When a user lifts the virtual dumbbell, the proposed system calculates the current lifting force through the velocity of the movements. The proposed system visualizes a circle-based gauge that indicates a gap between the standard and current lifting forces.

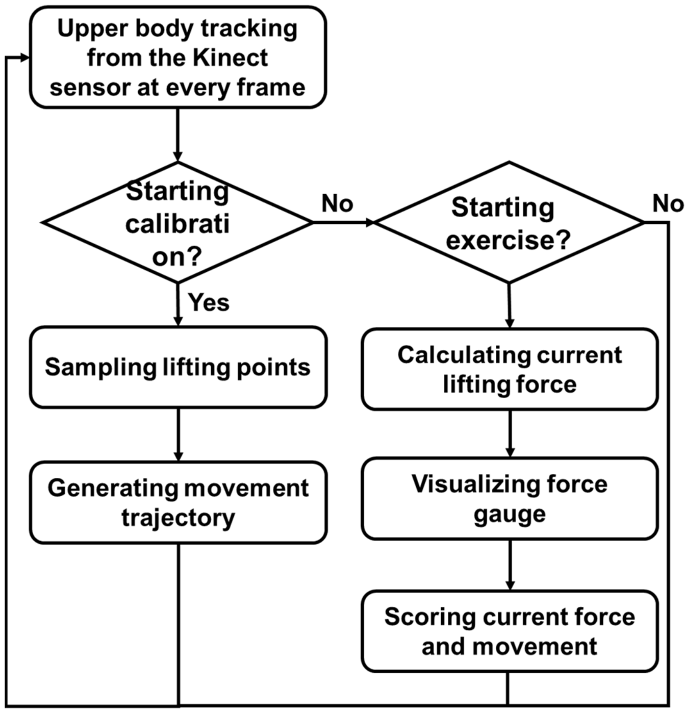

Figure 8. Process for the personalized weight perception interface.

5. Application

The proposed personalized weight perception method has been applied to VG simulation with different types of exercises where the user can grasp a virtual dumbbell and perceive pseudo-weight through visual feedback. The applications of VG are fitness care, game playing, and physical training in the real world.

As shown in Figure 9, VG system consists of three exercise scenarios: bicep, shoulder, and barbell bicep curl exercises. The proposed system visualizes three exercise scenarios when a user enters the VG (Figure 9). A user can select a specific exercise scenario by clicking one of the three virtual buttons associated with the exercise scenario (Figure 9).

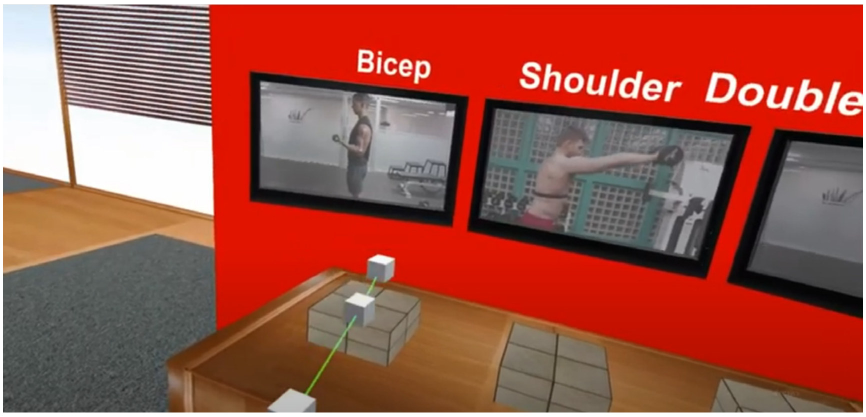

Figure 9. Proposed three exercise scenarios: dumbbell (bicep), shoulder, and barbell curl.

The three exercised contents utilized FGCGUI according to their characteristics. Because a user takes turns lifting his/her left- and right-handed dumbbells in the dumbbell curl exercise, the proposed system provides two FGCGUIs. Thus, the proposed system visualizes the left-handed FGCGUI when a user lifts a left dumbbell, as shown in Figure 10A. It also visualizes the right-handed FGCGUI when the user lifts the right dumbbell, as shown in Figure 10B.

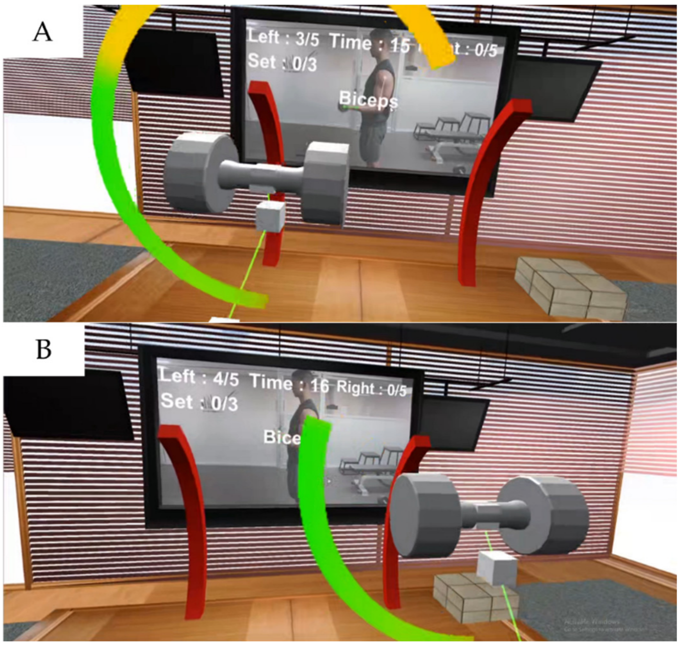

Figure 10. Dumbbell (bicep) curl process. (**A**) Left hand. (**B**) Right hand.

The proposed system slightly changes the standard joint from the elbow to the shoulder during the shoulder curl process (Figure 11). The arc-based movement trajectory also changes according to the changes in the shoulder curl process. Figure 11A,B show the left and right FGCGUI during a shoulder curl process. A user grasps with his/her two hands on the same barbell during the barbell curl process (Figure 12).

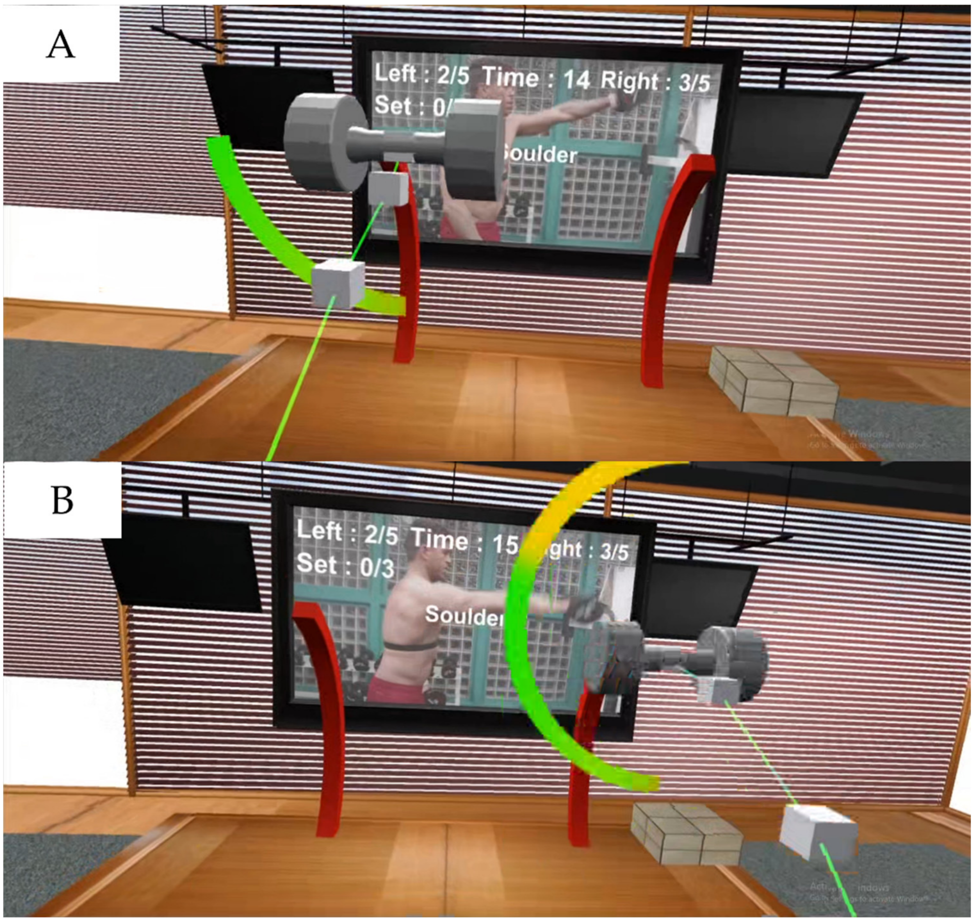

Figure 11. Shoulder curl process. (**A**) Left hand. (**B**) Right hand.

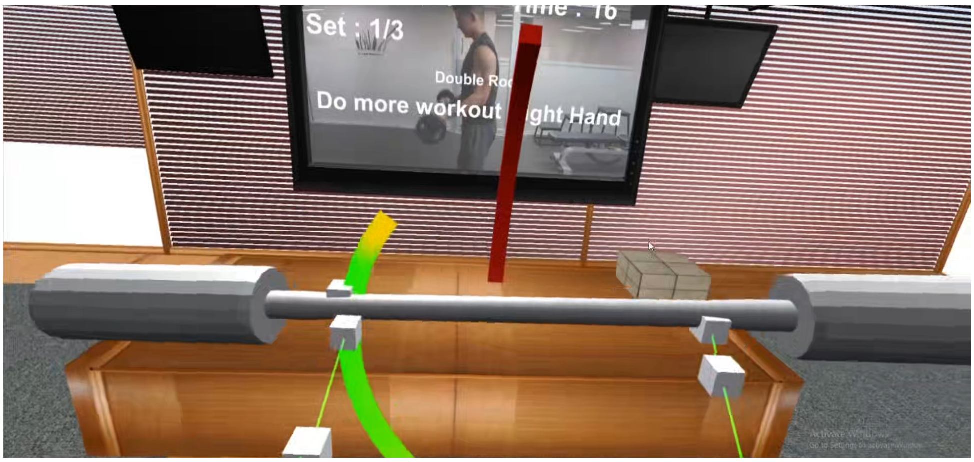

Figure 12. Barbell curl process.

6. User Study

6.1. Experiment 1-Comparing with Conventional Pseudo-Haptic Interfaces

Because the classical method for measuring presence uses questionnaires, we conducted the user study with the questionnaires. Participants were asked to live an experience of the pseudo-haptic interfaces, then they completed a questionnaire and give their feelings about their experience.

6.1.1. Materials

The experiments aimed to verify the usability of the weight perception of a user in a VG environment. Table 1 lists the environment of the experimental system.

Table 1. Experimental system environment.

Item	Value
VR HMD	Oculus Rift S
PC (Server)	i7-8700 CPU (3.2 GHz, 8 cores)/GTX2070
MR Software	Unity 2018.4(LTS)
Network	Local area network with 100 Mbps bandwidth

To evaluate the usability of the proposed weight perception interface, we compared the proposed FCGGUI with two other weight perception interfaces [19,20], with defined weight perception interfaces (Table 2). The "changing visual appearance" interface changes the size of the virtual object according to actual mass. Because the "changing visual appearance" interface is a primary pseudo-haptic interface, we selected it as a comparison target. We also decided on the "force arrow" interface because the "force arrow" controls the lifting velocity of the virtual object, which is closely related to the FCGGUI.

Table 2. Group of tasks.

Task	Pseudo Weight Interface
A	Changing visual appearance [19]
B	Force arrow [20]
C	FCGGUI

6.1.2. Weight Perception

Because the perception of participants is close to conducting a qualitative experiment, we designed two questionnaires to verify the usability of the proposed weight perception interface. We had two approaches to the usability of weight perception. We defined five weight-perception questions to focus on the perception of virtual weights. As part of this, we extended the conventional weight perception methods [20] with a general sense of presence questionnaire [30] (Table 3).

Table 3. Questionnaire on weight perception.

Number	Questions
WP1	Did you feel the weights of the virtual object?
WP2	Did the weight perception interface indicate lifting forces correctly?
WP3	Was it similar to experience of real lifting exercise?
WP4	Did you distinguish the weight differences of the virtual dumbbells?
WP5	Did you have an exercising feeling effect through the virtual dumbbell curl process?

6.1.3. Interaction

We defined five usability questions to compare the three weight-perception methods (Table 4). After completing the lifting process, each participant was asked to consider the 10 questions and give their opinions on a seven-grade scale, ranging from strongly disagree (1) to strongly agree (7).

Table 4. Questionnaire on usability of weight perception interface.

Number	Questions
U1	How well were you able to control the lifting process?
U2	How much did the control devices interfere with your performance in the lifting process?
U3	How satisfied are you with the weight perception interface?
U4	Is it easy to use?

6.1.4. Participants

We selected 15 participants aged between 20 and 40 years who had user experience in 3D VR environments. The participants were trained for 15 min in the basic usage of the proposed VG environment.

6.1.5. Procedure

We divided the participants into three groups and asked them to perform three tasks randomly to avoid errors in learning effectiveness. In Task A, the visual shape of the virtual dumbbell is changed according to its weight. The VG visualizes the current lifting force using a linear-based weight perception interface called "force arrow" in task B. The proposed FCGGUI was selected for Task C. Table 5 describes the order of the tasks.

Table 5. Order of tasks.

User Group	Order of Tasks
U1	A → B → C
U2	B → C → A
U3	C → A → B

Because conventional weight perception interfaces provided only one-handed weight perception interactions, the proposed system also used a one-handed weight perception interface in the experiment. The participants lifted two different weights of virtual dumbbells (5 and 10 kg, respectively) in the three tasks. One period of lifting curl consisted of ten lifting virtual dumbbells turns. Each participant performed three periods of lifting curls per virtual dumbbell weight. After three periods of lifting curls, a switch is made to a different virtual dumbbell weight.

6.2. Results of Experiment 1

6.2.1. Weight Perception

Figure 13 shows the results of the average points score from the participants' responses to the weight perception questionnaires. In terms of the results of weight perception question 1 (WP1), the FCGGUI was ranked first. Some participants perceived more weights of the virtual dumbbells when they followed the lifting force and movement trajectory according to the arc-based FCGGUI. According to the results of weight perception question 2 (WP2), the "force arrow" interface was ranked first because the liner arrow interface indicates accurate current lifting force. Although the "force arrow" interface was ranked first, some participants had difficulty matching indicated accurate forces during the lifting curl process. They were satisfied with the FCGGUI because matching the proper lifting force was easier than matching that of the force row. The results of weight perception question 3 (WP3) showed that the changing appearance of the virtual dumbbell was ranked first. Some participants were not satisfied with the "force arrow" interface because it was more annoying than the FCGGUI. The FCGGUI was ranked first in terms of the results of the weight perception question 4 (WP4). Participants could distinguish the real weights of the virtual dumbbells by controlling the lifting force. According to the results of weight perception question 5 (WP5), the participants perceived the real lifting exercise effects with the proposed FCGGUI. For statistical analysis, we conducted an analysis of variance

(ANOVA) test on the weight perception questionnaire results. Table 6 shows that the ANOVA test results for the average scores of the weight perception questionnaires for tasks A, B, and C were statistically significant ($p = 0.05$).

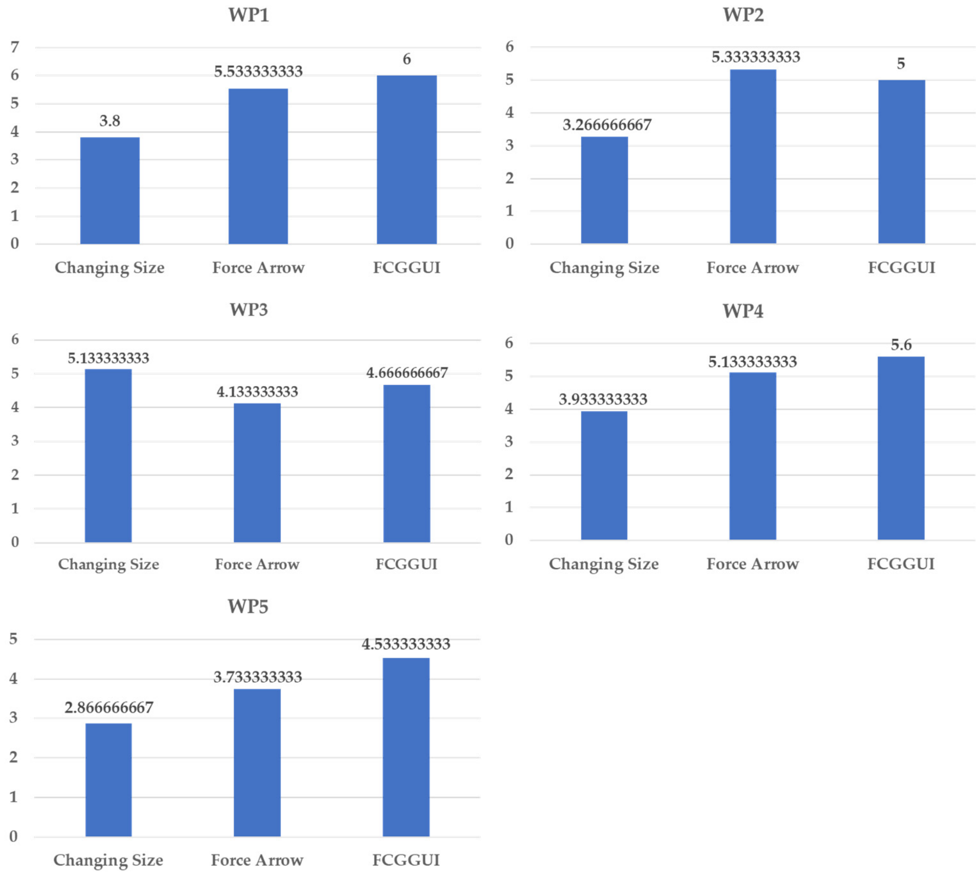

Figure 13. Results of the average points of questionnaires for the evaluation of weight perception.

Table 6. Results of the ANOVA test of the weight perception in Experiment 1.

Condition	ANOVA Result (pa = 0.05)	Mean and SD Results, Stored as in Figure 12
WP1	F = 28.09292, pa = 1.82×10^{-8} MSw = 0.71746	Changing Size (M = 3.8, SD = 0.8857) Force Arrow (M = 5.533333, SD = 0.695238) FCGGUI (M = 6, SD = 0.571428)
WP2	F = 38.26974, pa = 3.44×10^{-10} MSw = 0.48254	Changing Size (M = 3.26667, SD = 0.638) Force Arrow (M = 5.533333, SD = 0.38) FCGGUI (M = 5, SD = 0.428571)
WP3	F = 6.918, pa = 0.002529 MSw = 0.542857	Changing Size (M = 5.133333, SD = 0.552381) Force Arrow (M = 4.133333, SD = 0.4) FCGGUI (M = 4.466667, SD = 0.666667)
WP4	F = 16.47642, pa = 5.22×10^{-6} MSw= 0.673	Changing Size (M = 3.933333, SD = 0.78) Force Arrow (M = 5.133333, SD = 0.695238) FCGGUI (M = 5.6, SD = 0.542857)
WP5	F = 23.78986, pa = 1.24×10^{-7} MSw = 0.438	Changing Size (M = 2.866667, SD = 0.552381) Force Arrow (M = 3.733333, SD = 0.352381) FCGGUI (M = 4.533333, SD = 0.4)

6.2.2. Interaction

Figure 14 shows the results of the average points of the usability questionnaire measurements. Because participants had difficulty matching the accurate standard lifting force of the virtual dumbbells, they answered that the best interface in terms of control lifting force was the FCGGUI, according to the results of usability question 1 (U1). In terms of the interference of the weight perception interface during the lifting curl process, the participants were generally satisfied with the FCGGUI, according to the results of usability questions 2 (U2) and 3 (U3). Some participants advised that changing the appearance of the virtual dumbbells was lacking in terms of corresponding information to understand and help the lifting curl process. According to the results of usability question 4 (U4), the FCGGUI was lower than "force arrow." Some participants indicated a lack of understanding of the usage of the arc-based movement trajectory together with the circle-based force gauge. We conducted an ANOVA test on the usability questionnaire results for the statistical analysis. Table 7 presents the ANOVA test on the average scores of the usability questionnaire among tasks A, B, and C, which was statistically significant (p = 0.05).

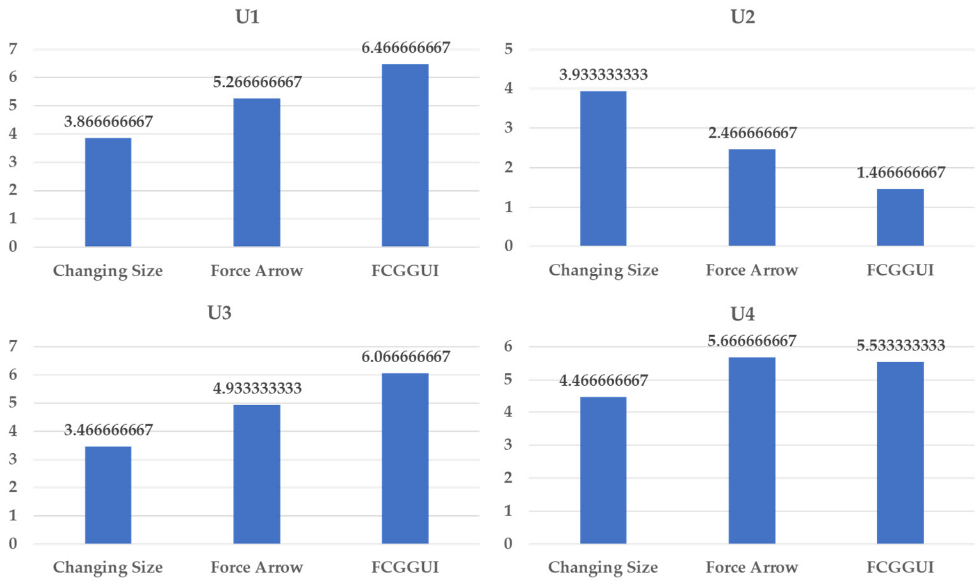

Figure 14. Results of average points of the questionnaire for the evaluation of user interaction.

Table 7. Results of the ANOVA test of the interaction in Experiment 1.

Condition	ANOVA Result (pa = 0.05)	Mean and SD Results, Stored as in Figure 13
U1	F = 47.625, pa = 1.59 × 10^{-11} MSw= 0.533333	Changing Size (M = 3.866667, SD = 0.552381) Force Arrow (M = 5.266667, SD = 0.638) FCGGUI (M = 6.466667, SD = 0.4)
U2	F = 47.53595, pa = 1.63 × 10^{-11} MSw = 0.485714	Changing Size (M = 3.933333, SD = 0.352381) Force Arrow (M = 2.466667, SD = 0.695238) FCGGUI (M = 1.466667, SD = 0.409524)
U3	F = 33.87764, pa = 1.74 × 10^{-9} MSw = 0.752381	Changing Size (M = 3.466667, SD = 0.4) Force Arrow (M = 4.933333, SD = 0.92381) FCGGUI (M = 6.06, SD = 0.86574)
U4	F = 6.679739, pa = 0.003 MSw = 0.971429	Changing Size (M = 4.46667, SD = 0.98) Force Arrow (M = 5.666667, SD = 0.952381) FCGGUI (M = 5.533333, SD = 0.9428)

6.3. Experiment 2—Two Handed Lifting

6.3.1. Materials

We conducted performance evaluations using the FCGGUI because it provides three types of two-handed lifting exercises. We conducted performance evaluations using the FCGGUI because it provides three types of two-handed lifting exercises. We asked participants the same questions as the weight perception and usability questionnaires described in Tables 3 and 4.

6.3.2. Participants

Fifteen different participants aged between 20 and 40 years were selected. After basic training on the proposed VG, the participants were divided into three groups to compare the three proposed two-handed lifting exercises.

6.3.3. Procedure

Table 8 lists the order of the three exercises (Figures 10–12). In the dumbbell and shoulder curl situations, the participants lifted two different weights, 5 and 10 kg. In terms of the barbell curl process, we defined two different weights: 10 and 20 kg. The participants performed three periods per weight of the dumbbell or barbell. The participants were asked to complete the same questionnaire about weight perception and usability after the lifting process.

Table 8. Order of exercising tasks.

New User Group	Order of Tasks
NU1	Dumbbell → Shoulder → Barbell
NU2	Shoulder → Barbell → Dumbbell
NU3	Barbell → Dumbbell → Shoulder

6.4. Results of Experiment 2

6.4.1. Weight Perception

Figure 15 shows the results of the weight perception questionnaire measurements for the three two-handed exercises. According to the results, the dumbbell curl process shows the best weight perception, and the barbell curl shows the worst weight perception. Because the participants could only lift one virtual dumbbell with their hand during the curl lifting process, they were generally satisfied with the dumbbell curl process. As the length of the movement trajectory was extended and the standard force increased in the shoulder curl process, the weight perception results of the shoulder curl process were slightly lower than those of the dumbbell curl process. Some participants had difficulty performing the barbell curl process owing to the challenge of perceiving the weights of the two hands simultaneously and recognition errors during the lifting process. Table 9 describes the results of the ANOVA test on the weight perception questionnaire for the dumbbell, shoulder, and barbell curls. The results were statistically significant (p = 0.05).

Table 9. Results of the ANOVA test of the weight perception in Experiment 2.

Condition	ANOVA Result (pa = 0.05)	Mean and SD Results, Stored as in Figure 14
WP1	F = 3.873, pa = 0.028594 MSw = 0.625397	Dumbbell (M = 5.933333, SD = 0.638) Shoulder (M = 5.533333, SD = 0.542857) Barbell (M = 6, SD = 0.695238)
WP2	F = 5.543147, pa = 0.0073 MSw = 0.625397	Dumbbell (M = 6.066667, SD = 0.749) Shoulder (M = 5.4, SD = 0.685714) Barbell (M = 5.133333, SD = 0.552381)
WP3	F = 4.7233, pa = 0.0141117 MSw = 0.653968	Dumbbell (M = 5.6, SD = 0.4) Shoulder (M = 4.933333, SD = 0.495238) Barbell (M = 4.7333333, SD = 1.066667)
WP4	F = 7.09396, pa = 0.002217 MSw = 0.473	Dumbbell (M = 5.8, SD = 0.457143) Shoulder (M = 5.466667, SD = 0.4) Barbell (M = 4.866667, SD = 0.552381)
WP5	F = 3.37931, pa = 0.043567 MSw = 0.7365	Dumbbell (M = 5.4, SD = 0.685714) Shoulder (M = 5.133333, SD = 0.695238) Barbell (M = 4.6, SD = 0.828571)

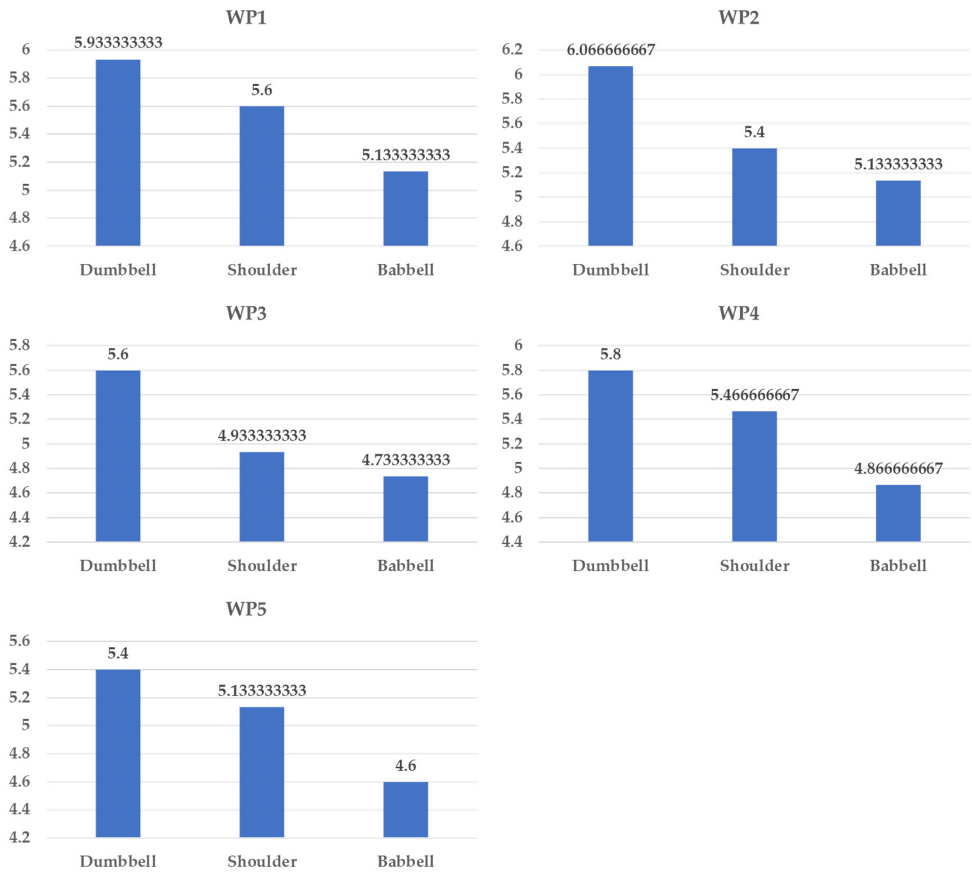

Figure 15. Results of the average points of the questionnaire for the evaluation of weight perception.

6.4.2. Interaction

Figure 16 shows the results of the measurement usability of the weight perception questionnaire for the three two-handed exercises. The participants were generally satisfied with the dumbbell-shaped curl process. Table 10 shows the results of the ANOVA test on the usability questionnaire, which were also statistically significant ($p = 0.05$).

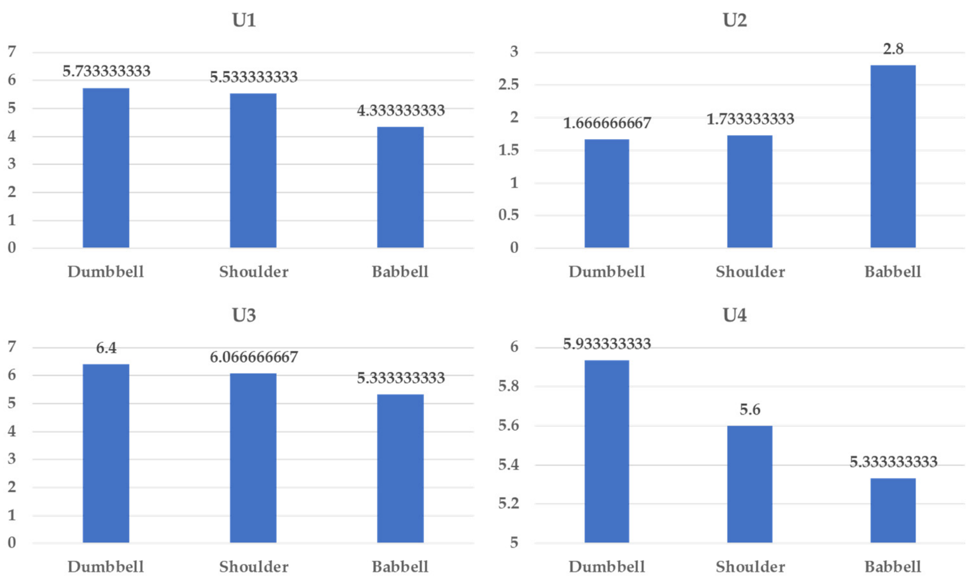

Figure 16. Results of average points of the questionnaires for the evaluation of user interaction.

Table 10. Results of the ANOVA test on the interaction in Experiment 2.

Condition	ANOVA Result (pa = 0.05)	Mean and SD Results, Stored as in Figure 15
U1	F = 13.89231, pa = 2.34×10^{-5} MSw = 0.619	Dumbbell (M = 5.733333, SD = 0.495238) Shoulder (M = 5.533333, SD = 0.552381) Barbell (M = 4.333333, SD = 0.809524)
U2	F = 17.37273, pa = 3.18×10^{-6} MSw = 0.349206	Dumbbell (M = 1.666667, SD = 0.238) Shoulder (M = 1.733333, SD = 0.495238) Barbell (M = 2.8, SD = 0.314286)
U3	F = 8.579268, pa = 0.000751 MSw = 0.520635	Dumbbell (M = 6.4, SD = 0.257143) Shoulder (M = 6.066667, SD = 0.495238) Barbell (M = 5.33333, SD = 0.809524)
U4	F = 4.797753, pa = 0.013286 MSw = 0.28254	Dumbbell (M = 5.933333, SD = 0.209524) Shoulder (M = 5.6, SD = 0.4) Barbell (M = 5.333333, SD = 0.238095)

6.5. Results of Performance Evaluations

Quantitative evaluations were also conducted during the second experiment. The average FPS is measured to verify the performance of the FCGGUI. The average recognition ratio was calculated using the pose estimation information of the participants and the errors. To measure the accurate gesture analysis of the tracked information, we measured the root mean square errors from the DBSCAN results. Figure 17 shows the performance evaluations. Because the experimental system environment was fixed, rending speed up to 60 FPS, the result of the average FPS was sufficient to use the FCGGUI in real time. Although the proposed system did not use recent deep-learning-based pose estimation or recognition algorithms, the recognition results were sufficient to provide weight perception in the simple lifting process.

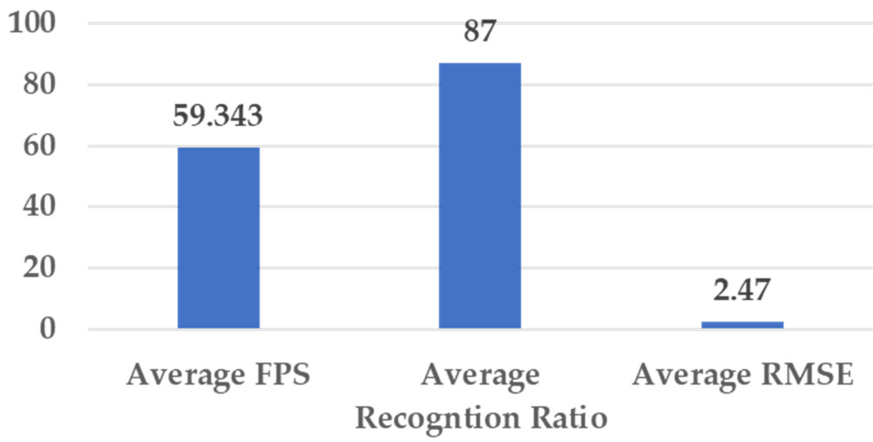

Figure 17. Results of the average points of the questionnaires for the evaluation of user interaction.

6.6. Experiment 3—Virtual Lifting vs. Real Lifting

6.6.1. Materials

Because the proposed system controls virtual lifting force based on control of lifting speed, another experiment is required to figure out between the force exerted by the user to lift the weight and the force required to lift the actual heavy object. To address this situation, we measured the exerted lifting force in both real and virtual lifting processes. The weight of the virtual and real dumbbells was set to 2.2 kg according to the opinions that users may be surprised or injured if they lift a real dumbbell that is too heavy while wearing a VR headset in the preliminary test.

6.6.2. Participants

We selected adult males between 25 and 30 for the experiment. Participants performed the virtual lifting dumbbell and the actual lifting dumbbell, respectively, and measured the EMG (electromyography) sensor value accordingly.

6.6.3. Procedure

Because the amount of muscle strength measured by the EMG sensor differs according to participants' physical characteristics, we performed a normalization process of the EMG sensor values. After the normalization process, the participants lifted the virtual dumbbell through FCGGUI first. Then, the participants lifted the actual dumbbell while the cognitive effect of the virtual weight remained. Participants could lift virtual and actual dumbbells for a total of 9 sets in sets of 10 repetitions. They were provided a 1-min break after completing one set of exercises to proceed similarly to the actual exercise.

6.6.4. Exert Force with EMG Sensors

In this experiment, an EMG sensor was used to measure the exerted force applied by the user to lift the object. The EMG signal is an electrical signal that appears according to the depolarization phenomenon inside and outside the muscle during muscle contraction and relaxation. We used the iEMG (integrated EMG), which is electromyography that can determine muscle activity through the cumulative result of muscle activity. The EMG Envelope can check information, such as muscle activity time, muscle activity period, instantaneous muscle activity, and muscle control pattern, through patterns that reflect changes in the state of muscle contraction [31].

Physiolab's PSL-IEMG2 module was used in the experiment. The output range is 0~3.3 V, and the EMG envelope can be output by changing the RawEMG signal. Figure 18 shows the output graph of the EMG value through the participant's biceps during the virtual lifting process. Because the magnitude of the force that participants can generate is different, the measured EMG sensor values of the participants were converted into values through normalization based on the minimum value of 0 and the maximum value of 1.

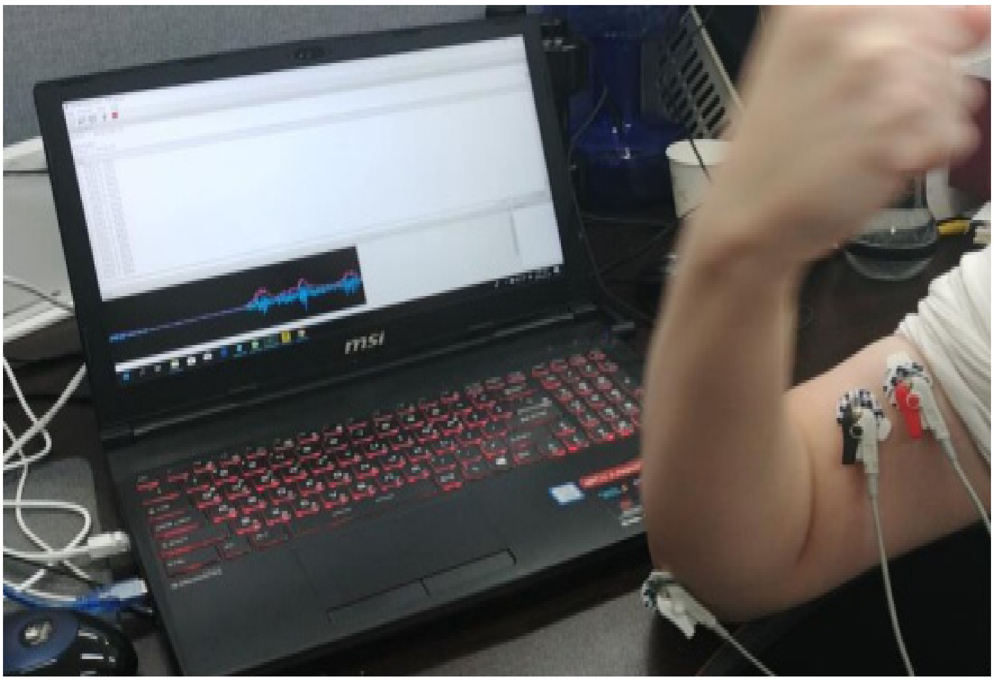

Figure 18. EMG sensor output while a virtual lifting process.

6.7. Results of Experiment 3Exert Force

Exert Force

Table 11 shows the average force used by the test participants measured during sets of 10 reps. When lifting a virtual object using FCGGUI, an average force of 0.1646 was used, and when lifting with actual weight, it was 0.22381, which is about 35.9% more than the virtual force. In addition, the standard deviation of the virtual force to lift a virtual object is 0.036225, which is more deviated than the standard deviation of the actual force required to lift a real object, 0.021803. This means that it is difficult to standardize because the deviation of the virtual force is larger than the actual force, even though the participants could perceive the weight of virtual dumbbells.

Table 11. Results of the average measured electromyogram.

Participants	FCGGUI	Real Lifting
P1	0.1171	0.2308
P2	0.1558	0.2406
P3	0.1326	0.2188
P4	0.1862	0.221
P5	0.2078	0.2636
P6	0.1418	0.1987
P7	0.2155	0.2414
P8	0.2036	0.2238
P9	0.1592	0.2104
P10	0.1264	0.189
Average	0.1646	0.22381
Standard Deviation	0.036225	0.021803

Table 12 describes the result of the ANOVA test on the force required for the user to lift. The virtual force of lifting the virtual object differs from the exertion force used to lift the actual object, and the gap between the virtual force and actual force was statistically significant (p = 0.05).

Table 12. Results of the ANOVA test of the exert force in Experiment 3.

ANOVA Result (pa = 0.05)	Mean and SD Results, Stored as in Figure 15
F = 19.61114, pa = 0.000324 MSw = 0.000894	FCGGUI (M = 0.1646, SD = 0.001232) Real Lifting (M = 0.22381, SD = 0.000475)

7. Discussion

7.1. Post Experiment about User Preferecens

We conducted a post-experiment of participants and performed user interviews with the 15 participants after the first experiment. We asked the participants about their preference for the pseudo-haptic interfaces. Figure 19A shows the results of the preference questions. According to the pseudo-haptic interface result, FCGGUI was ranked first (80%) and "force arrow" was ranked second. With the FCGGUI, the participants could control lifting forces with personalized movement trajectories. Thus, it was easier to perceive virtual weights during the lifting process. Participants who chose the "force arrow" interface mentioned that the "force arrow" showed an intuitive indicator of lifting velocity. The participants had problems perceiving the virtual weights with the "changing size" interface.

Some participants mentioned that a large-size virtual dumbbell felt lighter than other sizes of dumbbells.

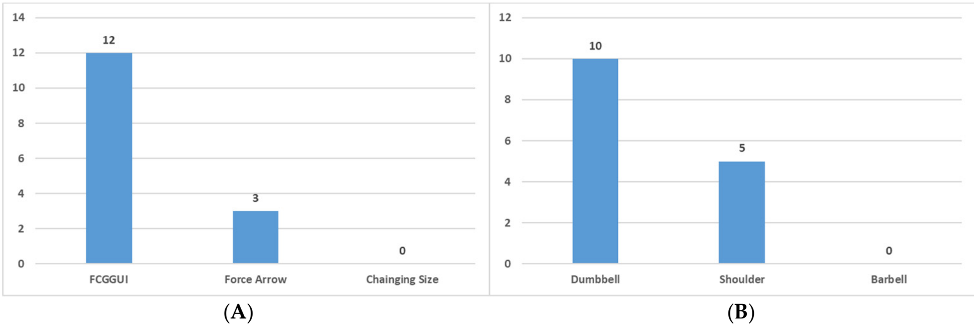

Figure 19. Results of the number of participants about the preference questions (**A**) answer to preference question of pseudo-haptic interface (**B**) answer to questions of two-handed lifting curl.

We also conducted user interviews with 15 other participants after the second experiment. We asked the participants about their preference for the three two-handed lifting curls. As shown in Figure 19B, the best-preferred exercise was the "dumbbell curl" process because the participants could control their left and right hands, respectively. Some participants said they best perceived virtual weights and felt exercise effects regarding the "shoulder curl" process. Regarding the "barbell curl" process, participants were confused about perceiving the same virtual weights on both hands.

7.2. Lifting Behaviors

According to the results of analyzing the behaviors of the participants, some participants' behaviors became abnormal when they lifted the virtual dumbbell. Figure 20A shows the abnormal behavior of a participant for whom the angles between the elbow and hand were incorrect. According to the user interview, he was too focused on controlling the current lifting force of a virtual dumbbell; thus, he did not realize that his lifting behavior was wrong. Furthermore, the participant mentioned that he could not perceive the proper virtual weight of the dumbbell. Figure 20B presents the normal behavior of another participant with the FCGGUI. The participants, who had wrong behavior in the changing size or force row method, observed the right behavior of lifting a virtual dumbbell. They provided feedback describing that they could perceive more weight using the FCGGUI method.

Figure 20. (**A**) Wrong behavior of lifting a virtual object in "Force Arrow." (**B**) Right behavior of lifting a virtual object in FCGGUI.

7.3. Exert Force and Limitations

We performed user interviews with the 10 participants after the third experiment. As a result of the interview, all of participants answered that they perceived the virtual weights of the virtual dumbbell when using FCGGUI. However, the participants answered that the force to lift a real dumbbell of the same weight differed from the virtual force applied to the virtual dumbbell. The participants were confused about how much force to apply to lift the virtual dumbbell. Although the proposed FCGGUI helped the participants by guiding lifting behavior with the movement trajectory and controlling lifting force with force graph visualization, participants lifted with much weaker force than the actual dumbbell.

The participants P5, P7, and P8 Table 11 showed that the virtual force using FCGGUI exceeded 0.2. The participants received personal fitness training regularly and tried to contract their muscles by giving strength to their arms as much as possible, even when lifting virtual weights. In addition, most of the participants who participated in other experiments complained of difficulty recognizing the virtual weight, complaining of a sense of heterogeneity due to the part where the exerted force was less than the actual weight in the case of virtual weight interfaces. Although the system proposed in this paper does not provide the part of increasing virtual force by contracting muscles in the interface, the participants mentioned that additional research and system expansion would be possible to reduce the gap lifting force between virtual lifting and actual lifting.

Some participants complained that recognition errors in upper-body tracking could affect weight perception.

8. Conclusions

In this paper, we proposed an FCGGUI to provide personalized weight perception for augmented virtuality serious games. To provide personalized weight perception, the proposed system provides an arch-based movement trajectory for the adaptation of size and position according to the user's body characteristics. The system also provides a circle-based lifting-force indicator for controlling the current lift force of virtual objects. The proposed FCGGUI interface was implemented and applied to a virtual fitness system, which could be one of the most promising applications of our approach. According to the results of user studies, the participants perceived enhanced weight perception and usability of virtual objects during the repetitive lifting process compared with conventional approaches. Furthermore, the proposed pseudo-haptic interface could improve the lifting behaviors of participants through the movement trajectory.

The proposed interface was applied to three two-handed lifting curls such as a dumbbell, shoulder, and barbell. According to the measurement results of the weight perception and usability of the proposed two-handed exercises, participants were generally more satisfied with dumbbell and shoulder curls consisting of separated two-handed grasping of virtual dumbbells. Although the barbell curl process showed lower weight perception and usability with the FCGGUI, the participants were still able to perceive the weights of the same virtual barbell. According to the result of the experiment on the exerted force through the EMG sensor value, the participants were aware of the virtual weight. However, the participants used a lower force than lifting the actual weight.

In future studies, we plan to overcome the current limitations of the proposed weight-perception interface. The following are some future research ideas:

(1) We will develop and apply a deep learning-based pose estimation algorithm and gesture analysis method to improve adaptation performance.
(2) We will also extend the proposed weight perception interface to more complex virtual object manipulations, such as collaborative lifting, moving, and installation.
(3) We will develop a simple pseudo-haptic hardware interface to measure the precise pressure force to provide exerting force for lifting virtual.

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