Virtual Exertions: a user interface combining visual information, kinesthetics and biofeedback for virtual object manipulation

Category: Research

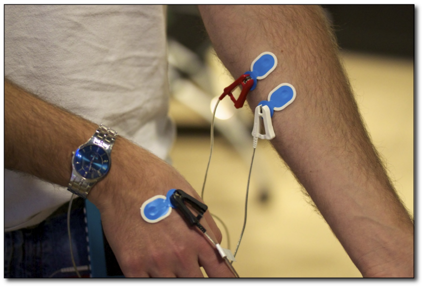

Figure 1: By using a combination of visual information, kinesthetics and biofeedback from electromyograms (EMG) users are able to grasp, move, and drop virtual objects.

Abstract

Virtual Reality environments have the ability to present users with rich visual representations of simulated environments. However, means to interact with these types of illusions are generally unnatural in the sense that they do not match the methods humans use to grasp and move objects in the physical world. We demonstrate a system that enables users to interact with virtual objects with natural body movements by combining visual information, kinesthetics and biofeedback from electromyograms (EMG). Our method allows virtual objects to be grasped, moved and dropped through muscle exertion classification based on physical world masses. We show that users can consistently reproduce these calibrated exertions when interfacing with objects in a novel way.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities H.5.2 [Information Interfaces and Presentation]: User Interfaces—Input devices and strategies

1 Introduction

Virtual reality environments utilize immersive experiences in an attempt to induce a feeling of presence [32]. While advancements such as in resolution and refresh rate may add to the immersive capabilities of a virtual reality system, they may not improve/strengthen the sense of presence for the user. For instance, a study by Slater, et al. found that presence is enhanced when interaction techniques are employed that permit the user to engage in whole-body movement [33]. Barfield and Hendrix reported that the level of interactivity between the subject and the virtual environment, rather than fidelity of the visual scene, was related to the perception of presence [2]. In this sense, in order for a virtual scenario to be effective, it must present an environment in which a person can interact naturally, intuitively and instinctively [7].

It is therefore beneficial for users to be able to grasp, hold, and manipulate objects in a virtual world as they do in the physical world. While determining if a collision has occurred between a virtual object and the user's hand is obtainable, determining if the user is attempting to grasp an object is a more difficult task [35]. Common methods to trigger a grasp event include button presses, hand gesture commands, and speech commands [23]. Of these three methods, only hand pose gesture recognition attempts to match natural interaction. Unfortunately, there are many different ways in which humans use their hands to pick up objects, and not all of them are recognizable with hand gesture systems, as shown by [35].

We present the idea of virtual exertions, a method utilizing biofeedback from electromyograms (EMG), along with visual and kinesthetic information, for the manipulation of virtual objects. Virtual exertions are defined as physical interactions with immersive virtual objects that are acted on through body motions and muscle contractions that mimic similar exertions against inertial objects in the physical world. This is unique, because interactions with virtual objects are not simply dependent on selecting objects with a wand or pointing device and moving them with gestures. Instead, users can control them with hand and body movements and muscles contractions similar to those used on objects in the physical world.

2 Previous Work

There has been a substantial amount of work on hand control for virtual object manipulation [27], [26], [19], [25], [4] and [35]. Bowman and Hodges evaluated various techniques for grasping and manipulating objects in virtual environments [6]. Techniques included extending virtual representations of arms and hands as well as using ray casting to manipulate objects. Schlattmann et al. provided a summary of interaction techniques for markerless handtracking [31]. For much of this work, users were required to fit their hand to a grasping pose to acquire an object as no information of the exertion forces could be ascertained [35]. Studies in which exertion forces are monitored have generally required fixed position input devices [21] [15]. While these devices have the ability to provide haptic feedback, their lack of mobility reduces the user's level of interactivity and immersion.

Other work has focused on multimodal methods of interaction techniques for the grasping of virtual objects [23], [5] and [17]. As most of these techniques required button or speech commands, the benefits of natural metaphors for interaction were lost [6].

Researchers have explored exertion interfaces, described as interfaces that require deliberate and intense physical effort [22] (Bragt provides a summary paper [7]). These interfaces range from users kicking balls at screens, hitting virtual baseballs, augmented ping-pong, virtually cycling and running. These interfaces increased the level of immersion for the participant as they allowed the user to utilize their senses. These systems not only provided interfaces that were more intuitive, but also generated new ways for the users to interact with the systems [7]. For example, Strömberg

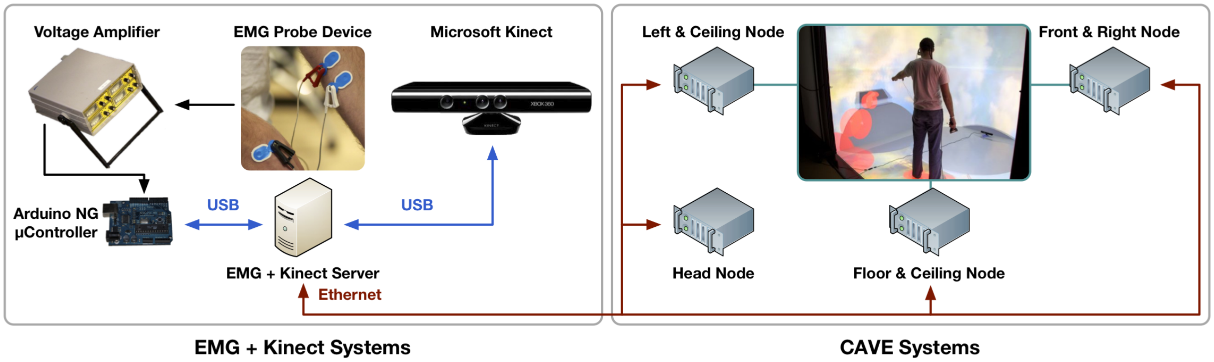

Figure 2: Diagram of the system architecture. The left-side demonstrates how devices were connected to our EMG and Kinect Server. This information was sent to the CAVE system (right -ide) via TCP communication. As shown on the right, a user is able to lift a virtual book (the aligned Kinect skeletal joints are shown in red).

et al. found that exertion interfaces allowed users to become more motivated or curious [34]. While these systems aimed to increase physical activity, level of exertion was seen as a result, not an input.

Other researchers have explored the idea of interfacing with EMG sensors for the purposes of human computer interaction. Costanza et al. have explored the idea of using EMG sensors to create intimate user experiences that analyze subtle movements [10] [12] [11] [13]. This allowed for the sensing of "motionless gestures" that could not be determined from outside observers. Saponas et al. [30] explored methods to classify finger gestures using a muscle sensing armband. Benko et al. used muscle sensing technology to further improve multitouch tabletop interfaces [3]. Saponas et al. [29] used forearm electromyography to classify finger gestures on a physical surfaces. Their system was able to interpret four-finger gestures with high degree of accuracy. Using 10 sensors, Saponas et al. were able to extend their work detect finger pressures and classify tapping and lifting gestures across all five fingers [28]. While these studies were mainly focused on gesture recognition and classification of physical world actions using EMG signals, we are interested in analyzing exertions as an interface for virtual environments.

3 METHOD

The goal of our method is to create an interface in which virtual objects react to hand and body movements and contraction of muscles similar to the manner these objects are acted on in the physical world. By using kinesthetic information and biofeedback, users have the ability to grasp, lift, move and drop objects. Unlike in previous work, our method gives virtual objects a sense of mass by requiring users to exert a calibrated amount of exertion in order to grasp and hold virtual objects. Additionally, users have the ability to grasp objects independent of the hand gesture, i.e. users can grasp objects without performing a grasping motion.

Our system is comprised of three major components: an EMG system, a Microsoft Kinect, and a Virtual Reality environment (Figure 2), each described below.

3.1 Biofeedback System

Exertions in the virtual environment were controlled by the level of muscle activity required for exerting corresponding forces on tangible objects. For this experiment, muscle activity of the flexor capri ulnaris muscle was monitored using surface EMG. Antagonistic muscles co-contract, resulting in static postures. Although no forces are exerted by the hands and body appendages, muscle activity mimic the intensity of exertions made when acting against physical objects. Co-contractions are normally involved in physical exertions. Brown and McGill (2008) observed a linear relationship in the EMG moment relationship of trunk muscles when measuring antagonist muscle co-activation.

The belly of the flexor capri ulnaris muscle was first located while a subject performed an isometric contraction holding a 4.5 kg load. Electrode positioning was performed according to the guidelines proposed by Mogk and Keir [20]. The position of electrode placement over the muscles were confirmed by palpation and signal response during specific exertions [20] [1]. The skin was cleaned with 90% isopropyl alcohol and allowed to dry for 1 minute. Silver-silver chloride electrodes were located over the muscle belly, parallel to the muscle fibers, with an inter-electrode distance of 2.5 cm. A reference electrode was placed on the dorsal side of the opposite hand, away from the electrically active area.

The surface EMG signals were amplified, integrated (IEMG), converted and sampled using an analog-digital converter connected to an Arduino NG microcontroller [16]. The IEMG signals are directly proportional to overall muscle activity and consequently to forces biomechanically linked to the limbs and torso [8]. The IEMG signals were calibrated using a series of exertions in the postures assumed when performing the task to be mimicked in the virtual environment.

3.2 Filtering

As the IEMG signals are very small in magnitude, they are generally filled with large amounts of noise. This noise can make classification difficult as it is hard to differentiate muscle exertions from noise. Kalman filters attempt to estimate "true" values by predicting a value, estimating the uncertainty of the predicted value, and computing a weighted average of the predicted value and the measured value [18]. This is done via a two step process consisting of a prediction and measurement/update step.

We apply a constant velocity Kalman filter in which we model the IEMG signal value and the derivative for the state variables. We determined all of the parameter values for our filter through empirical observations (for all data shown in this paper, $\sigma_a^2 = .004$, R = $1E^{-5}$and $\Delta t = 0.033$). As shown in Figure 3 this helped to reduce the noise on the IEMG signal.

In order to determine the amount of muscle exertion the user is expending, it is important to calibrate the system at startup. To do this, we measure the baseline IEMG signal while asking the user to remain at rest while taking samples for three seconds. We compute the average peak signal (B) over these samples in order to determine the bias point as shown.

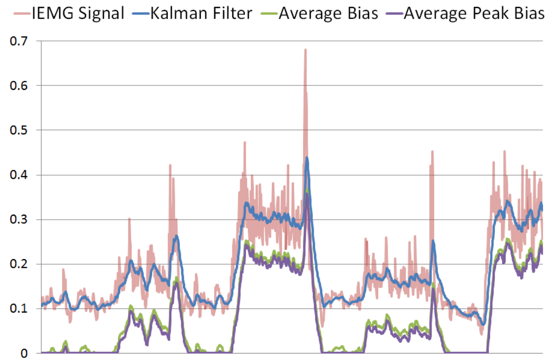

Figure 3: Filtering of an IEMG signal. The user followed the procedure of keeping their hand at rest, then gripping with normal exertion, rest hard exertion, rest, normal exertion, rest, hard exertion. The Kalman filter smooths the noisy result, but does not give information as to if the user is exerting force or not. The average peak bias correctly classifed data points (periods of inactivity are set to zero).

$$B = \frac{\sum_{x=1}^{n} p(x) f(x)}{\sum_{x=1}^{n} p(x)} \tag{1}$$

$$p(x) = \begin{cases} 1 & \text{when } f(x) > f(x-1) \\ 0 & \text{when } f(x) \leq f(x-1) \end{cases}$$

We selected peak-average value rather than a simple mean as it tended to produce a more representative baseline. As shown in Figure 3, this produces a better segmentation of action and non-action.

3.3 Calibration

To calibrate each user we monitored the IEMG signals while holding calibration objects, consisting of a masses weighing 0.74 kg (1.63 lbs), 1.13 kg (2.5 lbs), 1.36 kg (3 lbs), 2.27 kg (5lbs) and 4.54 kg (10lbs). The user was asked to grasp each object, hold it for five seconds and then release.

As shown by Brown and McGill [8], the amount of exertion force scales linearly with mass of the object. This simple linear conversion from mass to exertion force, enables each virtual object to be assigned a Minimum Exertion Force (MEF) value, representing the amount of force required to pick up and hold an object. Generally the linear fit equations had R^2 values greater than 0.99 in our testing. The method used to grasp, move and drop objects is described in Section **??**.

3.4 Kinesthetic System

In order to gain kinesthetic information, we chose to use the Microsoft Kinect system as it provided a low cost and unobtrusive means to capture information about about the user's posture. We used the Microsoft Kinect SDK Beta 2 (released November 1, 2011) to capture the skeleton of the user. As the Kinect SDK operates in its own reference frame, the positions of each skeletal joint is given as a distance from the Kinect camera. In order to use this information in the virtual space, we need to convert from Kinect space into virtual space.

We first physically align the Kinect system with the front wall of the CAVE system. This removes rotational discrepancies for the yaw and roll axis. Unfortunately, there still be rotational discrepancies in the pitch axis as shown in Figure 4. To correct for these, we calculate the the "up" direction as seen by the Kinect by asking the user to stand straight up and record the position of all of the joints. From this we create a vector from the center of the hip to the center of the shoulder that represents the user's "up" direction. We can then calculate the pitch rotational discrepancy (θ) as follows:

$$\theta = acos((P_{ShoulderCenter} - P_{HipCenter}) \cdot (0,0,1)) \tag{2}$$

Additionally, the positions of the joints must be corrected for. In order to create the virtual representations on the CAVE walls, the user must wear head tracking equipment. This gives a point of reference between the CAVE system and the Kinect system.

In order to make this space transformation efficient, we construct a correction matrix to multiply all of the Kinect skeleton joints by. In order to create our correction matrix, we first translate the Kinect joints relative to the head joint location (I, J, K), rotate about the x-axis (θ) and finally translate the joints in the virtual world to match the virtual worlds head location (X,Y, Z). Finally, as the Kinect system locates the middle of the head while the tracking system locates the users eyes, a small offset in the z direction must be applied (δ).

Therefore, the correction matrix K can be shown as:

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & cos(\theta) & -sin(\theta) & 0 \\ 0 & sin(\theta) & cos(\theta) & 0 \\ X-I & Y-Jcos(\theta)-Ksin(\theta) & Z+Jsin(\theta)-Kcos(\theta)+\delta & 1 \end{pmatrix}$$

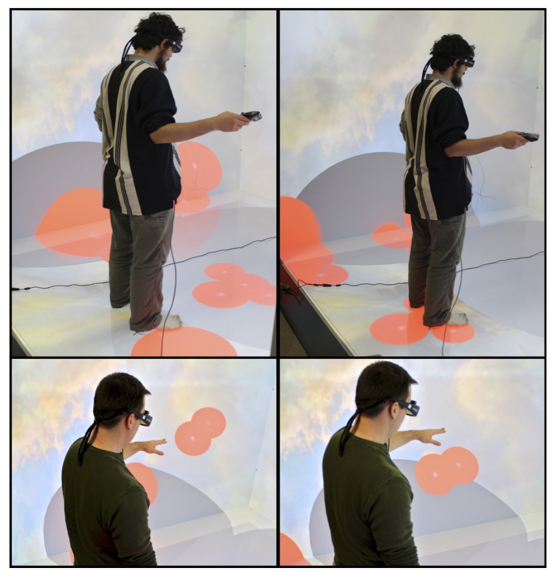

Figure 4: Comparing the uncorrected skeleton (left) with the skeleton after using the correction matrix (right). The skeleton joints (shown in red) are positioned in front of the viewer for the uncorrected version, while the joints are aligned with the viewer's perspective in the corrected version.

Figure 4 shows the Kinect skeletal joints (in red) before and after the correction matrix is applied. Before correction the skeleton appears to be tilted and in front of the user. After correction, the skeleton matches the user's virtual world perspective.

3.5 Virtual Reality Environment

The presented method is designed to work in a Cave Automatic Virtual Environment (CAVE). For the methods involved in this paper, it is necessary for the users to have the illusion that their hand can grasp virtual objects. Generally in order to achieve this effect, users must be head tracked and be receiving stereo 3D visual information. Head mounted display systems provide another way of generating these kinds of immersive experiences.

Additionally, the Kinect system will not obstruct the field of view for the user, improving immersion and reducing visual obstructions.

The CAVE system is comprised of four nodes, one head node and three render nodes, each running two walls of the CAVE environment. Each wall presents a resolution of approximately four megapixels. A separate data server acquires input from the Microsoft Kinect system and EMG interface, processes it and and forwards it to the CAVE system. In order to maintain synchronicity among all of the nodes, we developed a simple TCP communication system. Each node in the system requests information from the data server before starting its draw routine. Upon receiving the first request, the data server creates a copy of the current state of the input devices and sequentially sends it to the CAVE nodes.

Figure 5: User picking up a virtual bar of deodorant in a bathroom scenario with MEF of 0.05 determined by converting from the virtual mass.

Our VR software is built on top of the OpenSceneGraph [9], CaveLib [24] and Bullet [14] libraries. The CaveLib library provides mechanisms to synchronize the CAVE display systems and a means to generate the correct 3D user perspective based on the data returned from the head tracked system. The OpenSceneGraph library provides a mechanism to load 3D models. The Bullet engine was selected as it provides a means to create interactive physics in the virtual environment.

Virtual objects were given mass when loaded, and their physics properties were set to be dynamic in the physics engine, meaning that the position of the object was determined entirely by the physics engine. From the objects mass, the MEF value was determined from the calibration equation derived in Section 3.3. For instance, the deodorant shown in Figure 5 has a mass of 0.23 kg (0.5 lbs) resulting in an MEF of 0.05 for the given user.

Our method for grasping objects is similar to that of Zachmann [35]. First, we determine if there has been a collision between the virtual object and the hand. We represent the hand with invisible sphere of 5 cm in radius. After the skeleton alignment step described above, the physics engine performs the collision check [14]. If there is a collision, the state of the exertion ascertained by the Biofeedback System is compared against MEF. If the force being applied is greater than the MEF, the object is considered to be grasped, and its state in the physics engine is switched to kinematic. The kinematic state informs the physics engine that the movement of the object will now be based on user input, not the engine. If the exertion level of the user dips below the MEF value, the object is dropped, and its physical properties are switched back to being dynamic.

In addition to simply trying to match the constraints of physical world, our method can also augment them. As shown in [6], grasping objects can also be acquired via ray-casting, allowing users to manipulate objects from a distance. To accomplish this interaction paradigm, we created a ray from the user's elbow joint pointed to the user's hand which could be used to select objects. As opposed to pushing a button to "reel" an object in as shown in previous work, users can simply exert their muscles to the force of the object's MEF value. By doing this, the system applies a virtual impulse on the object, projecting the object towards the user's hand. This method was selected as we wanted to keep the object manipulation at the hand, as opposed to having the ray act as a virtual extension of the arm.

4 RESULTS

We created several different environments to test the system. The first environment consisted of two circular tables in which users were tasked with moving objects from one table to the other. The objects consisted of books and dumbbells, mirroring the physical objects the user can train with. We also utilized recreations of kitchen and bathroom environments (Figure 5. These environments were filled with everyday objects, such as tooth brushes, deodorant, soap, teapots, pans and cups that the user could manipulate.

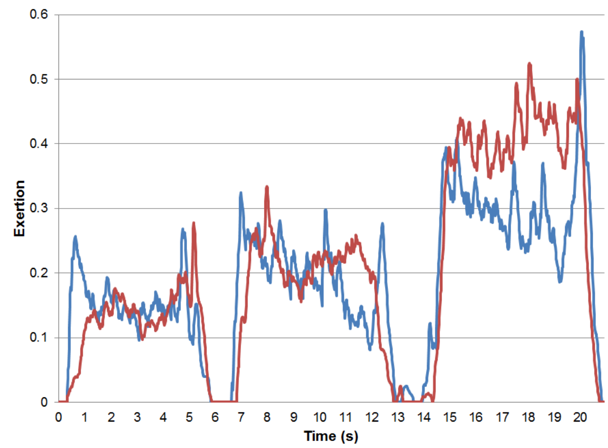

Figure 6: A demonstration of the exertion of a user lifting a physical object in blue and a virtual object in red. The response on the left represents an object of mass 0.74 kg (1.63 lbs), in the center an object of mass 1.36 kg (3 lbs), and on the right, an object of mass 2.27 kg (5lbs).

For the system to be effective, users needed to be able to virtually match the exertion that they would normally need to produce for lifting a physical object of equal mass. To test this, we had users lift objects of 0.74 kg (1.625 lbs), 1.36 kg (3 lbs), and 2.27 kg (5lbs) first physically, and then virtually. Figure 6 shows a graph of a these exertions for a user, with physical exertions shown in red and virtual exertions shown in blue. In general, users were able to generate a similar force for the virtual object as they would have used to lift the physical object.

It was also important to test the perceived latency of the system. To accomplish this we equipped the user with the EMG equipment attached to one hand and a wireless controller in the other. When the user intended to grasp a virtual object, they were asked to push a trigger button on the wireless controller. When the user wanted to drop the object, they were instructed to release the button. Table 1 shows the difference in time from when the pressed the button and the classification of the objects grasped state.

Method	0.74 kg (ms)	1.36 kg (ms)	2.27 kg (ms)
Grasp	20 (SD=44)	309 (SD=70)	359 (SD=100)
Release	32 (SD=100)	90 (SD=40)	5 (SD=5)

Table 1: The Grasp row shows the difference in time between when the user indicated they wanted to grasp an object and when the system classified the object's state as grasped. The Release row shows the difference in time between when the user indicated they wanted to release the object and the system classified the object's state as being dropped.

As shown, our method was most effective for lightweight virtual objects (< 1.13 kg (3 lbs)). For these objects, users were able to grasp the object with little latency compared to a simple button press. Dropping these objects generally worked effectively, but sometimes users flexed their hands on a drop, thus increasing their exertion for a short interval. This in turn created the appearance that objects were stuck to the hand for short periods of time. For objects of greater mass, the grasping stage incurred a much greater latency. This was due to the time needed for the user to reach the correct level of exertion. Dropping virtual objects with a greater MEF was generally easier for users, with very heavy objects being very low latency compared to a simple button press.

5 Discussion

Our system provides a means for users to interact with virtual objects using their own body movement and muscle exertions. This enables a more natural method of interaction, mimicking how users interact with objects in the physical world. Users were able to naturally catch objects out of the midair and were able to fling virtual objects across the computerized environments. As users needed to generate their own exertion through muscle tension, our method could be taxing. This was particularly the case for objects with a high MEF. For example, many users were unable to generate the MEF for lifting objects of mass 4.54 kg (10lbs) by simply using their own muscle tension.

Individuals familiar with the CAVE environment assisted in the development of this system. Most users were able to pick up objects without instruction after going through the calibration procedure. Users statements about the system were generally positive in nature, stating that they found the method of interaction easy and engaging. Many enjoyed the ability to manipulate objects independently of hand gesture. The major complaint given by users pertained to the wired EMG device, the prep work and the limitations of the movement. A wireless portable EMG system may be used in future work to mitigate these complaints.

While this system provides an initial proof of concept, further testing is still required. As this method uses the human body, a study of effectiveness over a broad population would be insightful. For instance, an understanding of how fatigue is incurred through only muscle tension without an opposing force would be necessary in order to make this interface more general purpose. Furthermore, an understanding of objects perceived locations in virtual environments is also necessary to enable a finer precision of object acquisition and placement.

Our prototype system is also somewhat cumbersome in its current state. While the wires attached the user's body are long enough to enable full traversal of the CAVE environment, users can still feel restricted. Wireless armband EMG devices have been prototyped by both Costanza et al. [12] and Saponas et al. [30]. These types of devices not only remove the wired connection, but also reduce the prep work that needs to take place before the system can be used. The user's movement is also somewhat restricted by the view of the Kinect camera. We believe that by adding and registering multiple Kinect camera devices, these restrictions could be greatly reduced. The system is also currently limited by the skeletal construction provided by the Kinect SDK. While currently the system can not capture hand poses, future research may be able to accomplish this with more sophisticated computer vision techniques.

As we only use the forearm muscles for the EMG testing, our system mostly captures gripping actions. For lifting cradled objects, the primary muscle group used for lifting may switch to the bicep. Thusly, in future work, it may be important to focus on multiple muscle groups. This would also enable users to lift objects with multiple hands. We believe the methods described in this paper for using the Kinect and EMG are still likely to be effective.

As more muscle groups are added, it may also be useful to use a classification system. This could also enable classification based not only on muscle exertion, but also with the users gestures and actions. This may provide a means of disambiguating gestures that appear similar based purely on movement. Also, as the force generated by the user is not square in nature, adding classification may give extra insight into the user's action. For instance, it may be possible to differentiate dropping from flicking from throwing.

Finally, since Virtual Reality environments provide visual cues that evoke a strong sense of presence, they are attractive for the study of behavior, for assessing designs, and for training in highly complex environments. Although virtual space differs from the physical world spaces in the absence of tactile and resistance cues afforded by actual objects, it affords the advantage of providing context for simulating visual cues from innumerable scenarios. For example, virtual environments can stress the participant with unplanned distractions, crisis situation or hazards. Alternately, they can create a safe space to test the psychomotor skills needed to carry out lifting, turning and pivoting interactions. A participant might be asked to lift an object of a certain load, but with a level of muscle exertion much greater than required for the real lift, thus imposing a virtual strength limitation.

6 Conclusion

This paper presents a novel interface for virtual environments by combining kinesthetic information and biofeedback from electromyograms (EMG). This method more closely matches the way people naturally interact with physical objects through grasping, moving and dropping without need for buttons, hand gestures or speech commands. Our method gives virtual objects the illusion of mass by requiring users to exert a calibrated amount of force to grasp and hold virtual objects. Users were consistently able to reproduce these calibrated exertions for manipulation of virtual objects of varying mass. Future work will focus on making the system more accessible to remove unnaturalness in the current setup and to provide a means for scientific experimentation.

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