Virtual Exertions: Physical Interactions in a Virtual Reality CAVE for Simulating Forceful Tasks

Robert G. Radwin, Karen B. Chen, Kevin Ponto and Ross D. Tredinnick
University of Wisconsin-Madison

This paper introduces the concept of *virtual exertions*, which utilizes real-time feedback from electromyograms (EMG), combined with tracked body movements, to simulate forceful exertions (e.g. lifting, pushing, and pulling) against projections of virtual reality objects. The user acts as if there is a real object and moves and contracts the same muscles normally used for the desired activities to suggest exerting forces against virtual objects actually viewed in their own hands as they are grasped and moved. In order to create virtual exertions, EMG muscle activity is monitored during rehearsed co-contractions of agonist/antagonist muscles used for specific exertions, and contraction patterns and levels are combined with tracked motion of the user's body and hands for identifying when the participant is exerting sufficient force to displace the intended object. Continuous 3D visual feedback to the participant displays mechanical work against virtual objects with simulated inertial properties. A pilot study, where four participants performed both actual and virtual dumbbell lifting tasks, observed that ratings of perceived exertions (RPE), biceps EMG recruitment, and localized muscle fatigue (mean power frequency) were consistent with the actual task. Biceps and triceps EMG co-contractions were proportionally greater for the virtual case.

INTRODUCTION

Using computer generated simulations to study human activities in various situations is an enticing approach. It could provide an interactive mechanism for allowing people to perform tasks in relative safety, for easily manipulating environments and conditions, for carefully instrumenting participant's actions, and for quickly prototyping new devices, tasks and environments. Immersive virtual reality (VR) simulations can work well when studying primarily cognitive tasks, but they are severely limited particularly when combining the cognitive with physical activities. Simulation of physical activities is important not only for research, testing and development, but also for training participants to perform physically demanding tasks safely, to prevent over exertions, or to avoid the hazards of falling. These applications range from training first responders, military personnel, laborers working in hazardous environments such as mines, to surgeons and physicians. Furthermore, computer generated simulations are increasingly being used for psychomotor conditioning and rehabilitation following injuries.

We define *virtual exertions* as a mapping of human-generated forceful actions, postures and movements that are generally used to manipulate physical objects, against projections of objects in the hands as an interface into the virtual environment. We hypothesize that virtual exertions can create the sensation of physical interactions with visual projections by moving and contracting the same muscles normally used for desired activities such as lifting, pushing or pulling, to suggest exerting forces. This is accomplished by measuring body kinematics through motion tracking instruments and muscle co-contraction activity through EMG electrodes affixed forearm and arm muscles and feeding back this information to the computer to cause the motion of the virtual object to respond according to the physical laws that allow them to visually react as they would if they were massive objects. We anticipate that having the participant use the same muscles as normally used in the real exertion task, creates the perception of physical resistance and invoke normal physiological responses such as muscle recruitment patterns and fatigue through voluntary antagonistic co-contractions in a VR simulation.

Previous studies have looked at direct interactions with virtual objects. Sutcliffe et al. (2006) studied user interaction with virtual chess pieces using pinch gloves in a CAVE based on the collision of the user's hand and the chess pieces. Another study explored human interactions with a ball in the "Virtual Catch Ball" large scale multi-projector system (Jeong et al., 2004). However, these methods did not incorporate opposition of forces or loads or friction as requirements for interaction.

There has been a substantial amount of work on hand control without monitoring exertion level for virtual reality object manipulation (Sanso and Thalmann, 1994; Rijpkema and Girard, 1991; Kijima and Hirose, 1995; Rezzonico, R. Boulic, 1995; Boulic, et al., 1996; Zachmann, 2000). Bowman and Hodges (1997) evaluated various techniques for grasping and manipulating objects in virtual environments. Techniques included extending virtual representations of arms and hands as well as using ray casting to manipulate objects. Schlattmann et al. (2009) provided summary of interaction techniques for marker-less hand tracking. For much of this work, users were required to fit their hand to a grasping pose in order to acquire an object as no information of the exertion forces could be ascertained (Zachmann, 2000). Work in which exertion forces are monitored generally require fixed position input devices (Monroy, et al., 2008; Ferre et al., 2010). While these devices have the ability to provide haptic feedback, their lack of mobility reduces the user's level of interactivity and immersion in the VR simulation.

It is well known that rectified surface EMG could approximate linear relationship with force produced by

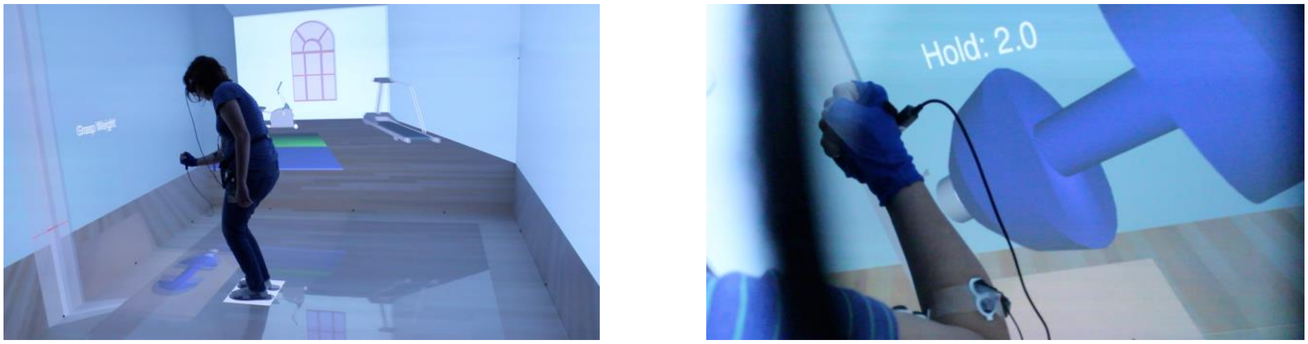

Figure 1. Photograph of a participant lifting a virtual dumbbell in a CAVE (left). An over-the-shoulder view is shown (right). In both photographs the participant observes the dumbbell through binocular vision so it appears to the user as if it is in their own hand. The EMG electrodes are on the arm and an ultrasonic position sensor is attached to a glove on the forehand.

muscles (Milner-Brown & Stein, 1974; Weir et al., 1994). Previous research found that rectified surface EMG could approximate linear relationship with force produced by muscles during isometric contraction (deJogn & Freund, 1967; Moritani and deVries, 1978). 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. These findings suggested relationships between EMG and forces, which makes it feasible for us to impart physical characteristics to the virtual objects, and then allow the manipulation of virtual objects based on the monitored EMG values.

The use of EMG signals in controlling and activation of objects have been implemented in prosthetics and robotics. This method was proposed as early as 1947 by Norbert Weiner (Bottomley, 1965). Battye et al. (1955) was the first to successfully control the movement of hand prosthesis, controlled by EMG, to grasp and hold a pencil. Bottomley (1965) has described the early hand prosthesis control mechanism as the activation of a pair of agonistic and antagonistic muscles. More complex EMG controlled prosthetic movements could be made possible with the additional EMG inputs of additional numbers of muscles to achieve the multiple degrees of freedom that a physiological hand has (Weir et al., 2006). Although EMG signals are capable in controlling prosthetics, there exist challenges such as skin and tissue impedance, noise and interference from the environment (Lai et al., 2007). Additionally, EMG signal characteristics vary according to the state of the muscles, such as muscle fatigue, and therefore resulting in a shift of EMG frequencies that might influence the identification of desired EMG signals for prosthetic activation. Furthermore, it has been identified that EMG could be used for controlling virtual arm movements displayed on computer screens for studying motor control, and even injuries (Manal et al., 2002; Manal & Buchanan, 2005).

METHODS

The virtual reality Cave Automatic Virtual Environment (CAVE) utilizes 12 active stereo 3D 1080p projectors capable of providing a 1920 ×1920 display on six surfaces that has four (4) rear-projection display walls, one (1) rear projection solid acrylic floor and one (1) rear projected ceiling (C6). The C6 uses a seven channel 6 DOF InterSense ultrasonic tracking system for full user viewpoint dependent stereoscopic viewing. Ultrasound emitters are embedded into the CAVE corners. Our CAVE supports a 144 Hz frame rate, which has the capability to provide stereo display to two independent viewers simultaneously by time multiplexing.

A pilot study was conducted using a simple EMG control algorithm involving the biceps muscle and hand location in order to demonstrate the feasibility of the virtual exertions. The EMG data acquisition system included a 16-channel EMG transmitter unit (Noraxon Inc), four EMG active leads with one ground lead, and a computer with custom programmed data collection software. EMG signals were transmitted to the CAVE computer at a 3000 Hz sample frequency. The position data acquisition system consisted of an ultrasonic tracker set (InterSense, Inc.) to allow full 6-DOF tracking. One tracker was mounted on the top rim of the CAVE shutter glasses to create images from the user's viewpoint, and another tracker was attached to a glove worn over the dominant hand to track the hand location.

Four participants (3 females and 1 male) were recruited for the pilot study with informed consent and IRB approval. EMG calibration was conducted at the beginning of each session. Participants performed a simple dumbbell lifting task using an actual dumbbell and a virtual exertion equivalent of the dumbbell lifting task in the CAVE. The system set up for virtual exertions is illustrated in Figure 1.

Bipolar surface EMG electrodes were affixed over the biceps, triceps, flexor and extensor carpi radialis muscles. The EMG signals were rectified and integrated (RMS). A calibration procedure involved lifting and holding various weights at different vertical heights. We observed that the biceps brachii EMG activity was proportional to load and had a quadratic relationship between muscle activity and the height at which the load was held at (Figure 2). This was anticipated due to the well-known muscle force-length relationship and is characteristic of the biceps. The relationship between triceps brachii activity was proportional to height (Figure 2).

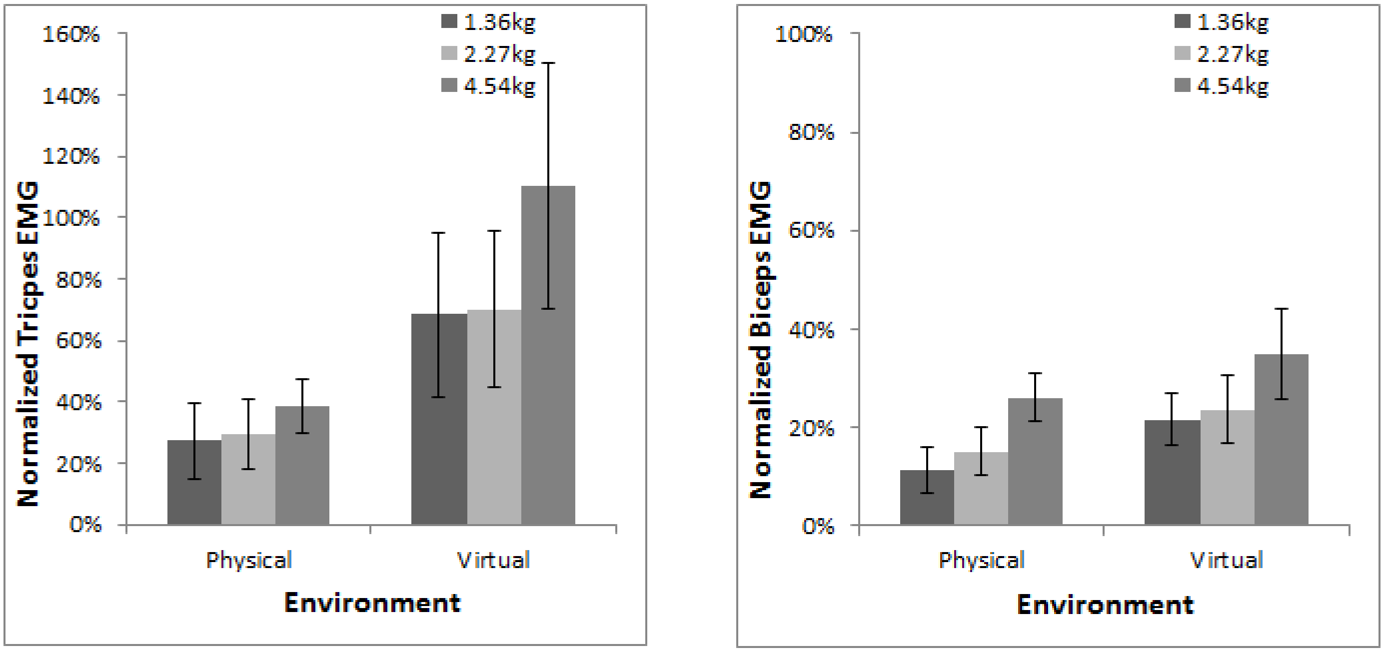

Figure 2. Increase in normalized triceps (left) and biceps (right) activity with respect to weight in different environments (±1 SE).

The movement of the virtual dumbbell was controlled according to the biceps EMG calibration curve and the location of the hand sensor. When the hand intersected the virtual dumbbell handle on the table, the subject was instructed to contract the biceps muscles and move the hand to lift it up to a given height. If the biceps EMG level was equivalent to the load of the dumbbell, the subject was able to lift the virtual dumbbell successfully.

Participants completed a total of two sessions that corresponded to the two environments, which were counterbalanced. Each session consisted of two activities; one weight lifting activity and one endurance activity. The weight lifting activity was a 2 × 3 × 3 (Environment × Weight × Height) mixed design where the participants completed three repetitions of each weight (3) and height (3) combination resulting in 27 trials. The endurance activity involved lifting and sustaining a 4.54kg (10lb) weight for two minutes.

The within-subject variables for the weight lifting activity were: environment, weight, and height. Environment was the only independent variable for the endurance activity. Environment included the physical and virtual environments. Weights were 1.36kg (3lb), 2.27kg (5lb), and 4.54kg (10lb). Heights were 91cm (36in), 107cm (42in), and 122cm (48in). The dependent variables were biceps and triceps activities, and RPE; additional dependent variables for the endurance activity included muscle fatigue mean power frequency (MPF) and mean amplitude at the first and last 10 s (time) of the endurance activity. All muscle activities were normalized against the participants' maximum voluntary contraction (MVC). ANOVA was used for evaluating statistically significant effects at an α level of .05.

RESULTS

Results from this study indicated that there was a significant main effect for weight for the triceps ($F[1,2]=37.27$, $p<.001$) and biceps ($F[1,2]=51.41$, $p<.001$) muscles, and RPE scores ($F[1,2]=25.53$, $p=.001$). Overall, muscle activity increased as the weight increased while statistically controlling for environment and height (Figure 2). A two-way interaction between environment and weight was observed for the triceps ($F[1,2]=14.61$, $p=.005$), and biceps ($F[1,2]=12.68$, $p=.007$) muscles. This suggests that the change in muscle activity was significantly different between the two environments (Figure 2). The three-way interaction was statistically significant for RPE ($F[1,4]=3.58$, $p=.038$) (Figure 3).

Endurance activity analysis indicated that there was a significant effect of time on biceps MPF ($F[1,1]=10.81$, $p=.046$) (Figure 4).

DISCUSSION

One requirement for virtual exertions is that the users perceive they are exerting forces in the virtual task commensurate with exertion levels for the actual task. Consequently participants should perceive they are exerting force proportional to the load. The psychophysical measure, rating of perceived exertion (RPE) where participants subjectively rated their exertion level was consistent for both the physical and virtual conditions.

The question at hand is not whether we can simulate realistic challenges within a fully-immersive visually intense virtual space, but rather can virtual exertions provide a more natural interface for simulating physical tasks in a CAVE virtual reality environment. A virtual exertion does not necessarily need to recreate the experience of the real activity; it merely needs to provoke the participant into behaving in a way similar enough to the way they would behave in the real situation such that a mapping will be possible. The current study measures perception (RPE) as well as involuntary physiological responses (EMG) as an indicator of presence.

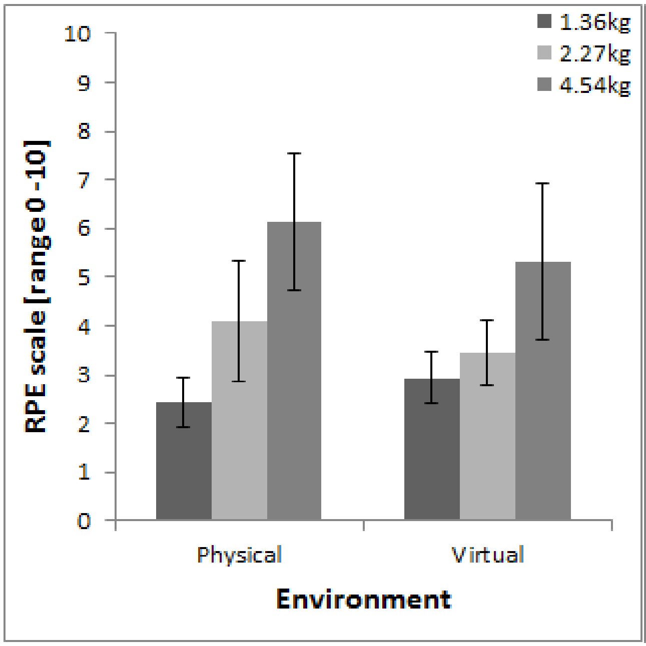

Figure 3. Ratings of Perceived Exertions (RPE) v. environment.

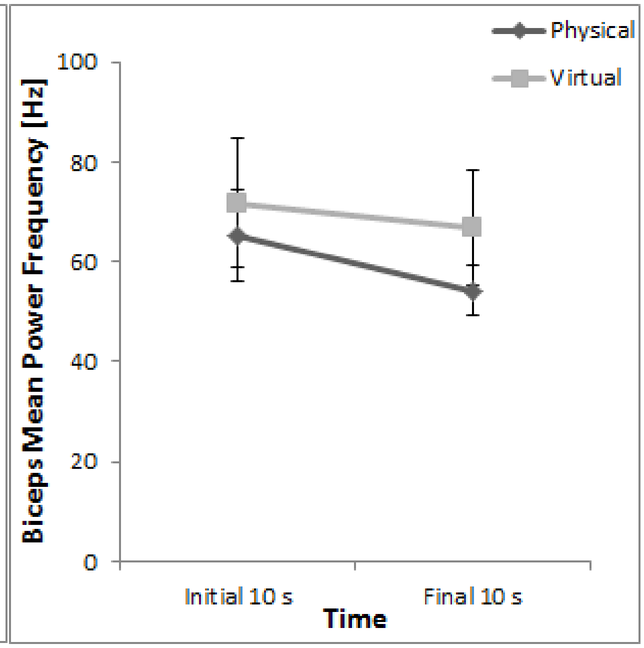

Figure 4. Interaction between mean power frequency and time.

We believe that physical interactions with visually projected objects that provide sense of weight of an object in one's hand while lifting using the actual muscle groups involved in force generation are important features that would enhance the user experience and the sense of presence in a virtual environment, which would provide a simulation that better represents the characteristics of the physical world. One way to provide user feedback on object weight and gravity is by bringing in a physical item to VR. Users touched a physical object and the movement of the physical object was tracked by sensors and in return controlled the movement of the same virtual object seen in the HMD (Hoffman, 1998). This required an actual physical item in VR, and it would not be practical to have physical objects in VR for all items that needed to be interactive, nor could user's precisely see their own body and hands, which is critically important for performing dexterous activities.

The differences observed in physiological responses reveal an important distinction between the real task and the virtual simulation. In this case, although the prime movers (biceps) were consistent in their activity level for both the real and VR case, the antagonists (triceps) contracted at much greater levels than for the physical task. Since the EMG control algorithm was based on biceps muscle activity for moving the dumbbell, the biceps muscle activity level was forced to correspond with biceps muscle activity for the real task. Using biceps activity as the threshold for the VR object control algorithm during a co-contraction however, resulted in much greater triceps activity for antagonistic muscle compensation. This is anticipated biomechanically since the insertion of the triceps muscles provides a much smaller moment arm than the opposing object in the hands, and therefore the triceps must generate greater forces in order to produce the same elbow moments as the real task. In some cases triceps contraction in the virtual case exceeded 100% MVC for actual pulling, evidently because different muscles are recruited (Figure 2) for the co-contraction exertions. But since the RPE was consistent with the real task, it is anticipated that the participant was focused on the biceps and hence perceived the VR task in a similar manner to the real task, disregarding the additional triceps activity. How these physiological differences might actually alter behavior in a more complex simulation, or be constrained is the topic of future study.

Better control algorithms also need to be explored. Multiple muscle groups might actually be recruited in more complex exertions and therefore control algorithms utilizing muscles might improve the simulation. Moreover, participants only received visual feedback in VR and limited haptic feedback which may have altered the participants' responses.

The results from this pilot study are encouraging and bolster our further exploration into the use of VR for simulating not only cognitively but also physically demanding tasks. We think that virtual exertions might help contribute to better training as well as providing a safer way for conducting laboratory studies in human factors and ergonomics. Finally, we anticipate that virtual exertions might be useful for physical training and rehabilitation.

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