Virtual Exertions: Evoking the Sense of Exerting Forces in Virtual Reality Using Gestures and Muscle Activity

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Objective: This study was a proof of concept for *virtual exertions*, a novel method that involves the use of body tracking and electromyography for grasping and moving projections of objects in virtual reality (VR). The user views objects in his or her hands during rehearsed co-contractions of the same agonist-antagonist muscles normally used for the desired activities to suggest exerting forces.

Background: Unlike physical objects, virtual objects are images and lack mass. There is currently no practical physically demanding way to interact with virtual objects to simulate strenuous activities.

Method: Eleven participants grasped and lifted similar physical and virtual objects of various weights in an immersive 3-D Cave Automatic Virtual Environment. Muscle activity, localized muscle fatigue, ratings of perceived exertions, and NASA Task Load Index were measured. Additionally, the relationship between levels of immersion (2-D vs. 3-D) was studied.

Results: Although the overall magnitude of biceps activity and workload were greater in VR, muscle activity trends and fatigue patterns for varying weights within VR and physical conditions were the same. Perceived exertions for varying weights were not significantly different between VR and physical conditions.

Conclusions: Perceived exertion levels and muscle activity patterns corresponded to the assigned virtual loads, which supported the hypothesis that the method evoked the perception of physical exertions and showed that the method was promising.

Application: Ultimately this approach may offer opportunities for research and training individuals to perform strenuous activities under potentially safer conditions that mimic situations while seeing their own body and hands relative to the scene.

Keywords: simulation and virtual reality, electromyography (EMG), forces and moments, computer interface, virtual environments

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INTRODUCTION

Simulation of physical activities is important not only for research, testing, and development but also for training individuals to perform physically demanding tasks safely, preventing overexertions, or avoiding the risks of falling. Immersive virtual reality (VR) has been demonstrated useful for numerous training and simulation applications involving physically demanding activities, including emergency medicine and disaster preparedness (Andreatta et al., 2010; Reznek, Harter, & Krummel, 2002), crowd evacuation from an area under a terrorist bomb attack (Shendarkar, Vasudevan, Lee, & Son, 2006), manufacturing processes (Mujber, Szecsi, & Hashmi, 2004), posttraumatic stress disorder and stress inoculation training (Wiederhold & Wiederhold, 2008), physical rehabilitation (Henderson, Korner-Bitensky, & Levin, 2007), mining (van Wyk & de Villiers, 2009), Tai Chi training (Chua, et al., 2003), and maintenance of industrial equipment (Oliveira, Cao, Hermida, & Rodríguez, 2007). Bailenson et al. (2008) have shown that immersive VR was superior for training individuals to perform physical movements, such as physical therapy and exercise, compared to video training according to objective performance measures.

While simulation studies in VR provide safe experimental conditions to mimic images and situations and to explore human behavior, virtual objects created by computer graphics lack weight and force feedback. Unlike in the physical environment, individuals produce forces by muscle contraction to counter the forces of physical objects. A common control device used for manipulating virtual objects in a Cave Automatic Virtual Environment (CAVE) is a hand-operated controller or a "wand." As a result, users may not experience the usual physiological reactions, such as appropriate muscle contraction, force production, and exertions, in response to weight and forces in VR. Various techniques have been developed to introduce force and haptic feedback, such as a penlike device (PHANToM™) that exerts a force vector on the fingertip of the user, incorporation of tangible physical objects into the virtual environment, an actuator-based tactile feedback device (FEELEX), and a wearable haptic hand or fingered gloves that provide resistive forces or shear stress (Bau & Poupyrev, 2012; Burdea, 2002; Burdea, Popescu, Hentz, & Colbert, 2000; Connelly et al., 2010; Iwata, Yano, Nakaizumi, & Kawamura, 2001; Minamizawa, Kajimoto, Kawakami, & Tachi, 2007; Popescu, Burdea, Bouzit, & Hentz, 2000; Sallnäs, Rassmus-Gröhn, & Sjöström, 2000).

These types of force and haptic feedback rely on additional devices or small physical objects that are specifically made for that task. Users are sometimes bound to a fixed location in order to receive feedback from immobile instruments, which may limit the integration of the task into the virtual scenario. Moreover, these devices mostly focus on feedback to the hand region, and thus providing force feedback for tasks involving gross motor activity may be challenging. Therefore, we are motivated to incorporate a mechanism in VR that suggests muscle contraction when directly manipulating virtual objects without control devices.

In this study, we explore if we can create more evocative experiences of muscle contraction during a physical task when interacting with virtual objects through the concept of *virtual exertions*, a method utilizing biofeedback from electromyograms (EMG) as well as gestures and movements for interacting with virtual objects in VR. Our experience in creating VR scenarios in a CAVE finds that this feature is an important aspect of the simulation that currently lacks a practical solution. The objective of virtual exertions is not to faithfully simulate physical exertions in VR but rather to devise a methodology for evoking the sense that one is exerting forces in a VR simulation. Correspondingly, VR simulations could include physical tasks alongside cognitive activities for observing participant behaviors and for experiencing tasks for training and research without the risk of injuries or falls. Examples of such applications involve activities performed by factory workers, first responders, and those in military, mining, manufacturing, and many other both cognitively and physically demanding jobs.

Physical exertions are the contraction and expenditure of energy by skeletal muscle groups in the physical environment for doing mechanical work against a load and for performing gross- or fine-motor tasks. 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. In order to create virtual exertions, EMG activity is monitored during rehearsed co-contractions of agonist-antagonist muscles used for specific actions, and contraction patterns and levels are combined with tracked motion of the body and hands for identifying when the participant is exerting sufficient force to displace the intended object in a CAVE. EMG electrodes affixed to the forearm and arm muscles feed back this information to the computer to cause the motion of the virtual object to respond according to the physical laws that allow the virtual objects to visually react as they would if they were massive objects.

Simulated resistance to virtual objects comes directly from co-contracting antagonist muscles that stiffen the joints. Hogan (1984) demonstrated that humans co-contracted both biceps and triceps in an isometric elbow flexion posture while grasping a 5-lb weight, which represented a usual task under normal physiological conditions. It was suggested that co-contraction contributes to postural stabilization even during a weight-bearing task in the physical environment. Furthermore, continuous visual feedback is provided to the users of virtual exertions to display mechanical work performed against virtual objects with simulated inertial properties. Virtual exertions may be a more evocative method of interfacing humans and virtual objects because they involve the expenditure of energy by common muscle groups used for physical tasks, although absent of external resistance or loads.

It is well known that rectified surface EMG approximates the linear relationship with force produced by muscles during isometric contraction

(De Jong & Freund, 1967; Milner-Brown & Stein, 1975; Moritani & DeVries, 1978; Weir, Wagner, & Housh, 1992). Muscle torque and integrated EMG signals are generally linear in the forearm flexors and the leg extensors (Weir et al., 1992). However, some studies have shown that summation of muscle-unit EMG potentials is nonlinear at high force levels or a general nonlinear relationship between EMG and muscle tension (Milner-Brown & Stein, 1975; Zuniga & Simons, 1969). These findings suggested direct relationships between EMG and forces, which makes it feasible for us to impart physical characteristics to the virtual objects and thus allow the manipulation of virtual objects based on the monitored EMG values.

The use of EMG signals in controlling and activation of objects, similar to the virtual exertions concept in VR, has long been implemented for prosthetics and robotics. This method was proposed as early as 1947 by Norbert Weiner (Bottomley, 1965). Battye, Nightingale, and Whillis (1955) were 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-antagonistic muscles. It required the myoelectric signal of the flexors to activate the closing movement of the prosthetic hand, and then it was necessary for the activation of the extensor myoelectric signal to relax the grasping movement. 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, Troyk, DeMichele, & Kerns, 2006). 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 & Buchanan, 2005; Manal, Gonzalez, Lloyd, & Buchanan, 2002).

Previous researchers have explored the idea of interfacing with EMG sensors for the purposes of human–computer interaction. Costanza and colleagues (Costanza, Inverso, & Allen, 2005; Costanza, Inverso, Allen, & Maes, 2007; Costanza, Perdomo, Inverso, & Allen, 2004) have explored the idea of using EMG sensors to create intimate user experiences that analyze subtle movements. This method allowed for the sensing of "motionless gestures" that could not be determined from outside observers. Whereas these works are mainly focused on gesture recognition and classification of physical actions using EMG signals, we are interested in using graded exertions as an interface for virtual environments where users interact directly with virtual objects in their hands using postures, muscles, and poses typically assumed for the simulated task.

Another motivation for virtual exertions is to permit users in VR to be able to see flexibly virtual objects manipulated directly in the hands and to possibly improve user performance in VR. Our previous research has compared user physical interaction between physical objects and equivalent stereo virtual objects presented in a CAVE using a target location task to examine how human performance (accuracy, time, and approach) is affected by various target locations (Chen et al., 2014). Fourteen participants completed a manual targeting task that involved reaching for corners on equivalent physical and virtual boxes in three different sizes. Users were 1.64 times less accurate ($p < .001$) and spent 1.49 times more time ($p = .01$) in targeting virtual than physical box corners. Consequently, we think that the alignment of visual feedback, among other visual factors and physical actions, is important for creating a plausible physical simulation, which led to the concept of virtual exertions—seeing a virtual object in the hand of the user and co-contracting to interact with it. We anticipate that some of these discrepancies stem from incorrect geometric viewing parameters, specifically, that physical measurements of eye position are insufficiently precise to provide proper viewing parameters (Ponto, Gleicher, Radwin, & Shin, 2013). Consequently, we investigate the effects of VR immersion (i.e., 2-D bland visuals vs. 3-D stereo visuals) in the current study.

This study is a proof of concept of the virtual exertions method for simulating the handling of virtual objects. Participants performed simple biceps curl dumbbell-lifting tasks in both the physical and immersive virtual environments.

TABLE 1: Participant Demographics and Characteristics

Variable	*n*
Gender	
Female	8
Male	3
Age (*SD*)	24.5 years (3.53)
Height (*SD*)	170.25 cm (11.62)
Interpupillary distance (*SD*)	61.92 mm (3.73)
Handedness	
Left-handed	2
Right-handed	9
Vision	
Corrected to normal	9
Normal	2

It was hypothesized that virtual exertions can create responses of physical interaction against visually mediated objects by moving and contracting the same muscles normally used for activities including lifting, pushing, or pulling to suggest exerting forces. We also tested the hypothesis that users' performance in VR that has a greater level of immersion will be closer to their performance in the physical environment. Both physiological (EMG) and psychophysical (ratings of perceived exertion and task load) responses were recorded.

METHOD

Participants

Eleven participants were recruited from the University of Wisconsin–Madison campus with informed consent and having the demographics summarized in Table 1. Inclusion criteria were self-reported normal or corrected-to-normal vision, willingness to continuously lift a 4.54-kg (10-lb) weight for 2 min, and ability to stand for at least 20 min. Exclusion criteria comprised self-report of neuromotor impairments, claustrophobia in a 3 m × 3 m × 3 m cubic room, Lasik eye surgery, experiences of epileptic seizure or blackout, a tendency for motion sickness when experiencing visual motion conflicts, sensitivity to flashing lights, or taking perception-altering medication. One participant did not complete one of the 2-D virtual environment sessions out of the three sessions required. All participants were of at least 18 years of age.

Instrumentation

VR CAVE. The virtual scenarios (3-D stereo and 2-D bland) were created in a 2.93 m × 2.93 m × 2.93 m six-faced (C6) rear-projection CAVE that consisted of one ceiling, one solid acrylic floor, and four walls (Figure 1). Two 3-D projectors (Titan Model 1080p 3D, Digital Projection, Inc., Kennesaw, GA) with maximum brightness of 4,500 lumens per projector, with a total of 1,920 × 1,920 pixels combined, projected images on each surface of the CAVE. The projectors refreshed at 144 Hz frame rate, which had the capability to provide stereo display to two independent viewers simultaneously by time multiplexing. The visuals were either retrieved from an online open-source 3-D model repository (Trimble 3D Warehouse, Google, Mountain View, CA) or created in SketchUp (SketchUp, Trimble Navigation, Ltd., Sunnyvale, CA), and then the virtual scenarios were rendered by a set of four workstations (2 × Quad-Core Intel Xeon). Shutter glasses (CrystalEyes 4 Model 100103-04, RealD, Beverly Hills, CA) were worn to view images in stereoscopy. Audio was generated by a 5.1 surround-sound audio system.

Tracking. Position data were acquired using a wireless ultrasound tracking system (VETracker Wireless 6R36 Model IS-900, InterSense, Inc., Billerica, MA), which included two position trackers (MicroTrax Model 100-91300-AWHT, InterSense, Inc., Billerica, MA) and 30 ultrasound emitters that were evenly embedded along the upper (two per edge) and vertical (three per edge) edges of the CAVE to allow full 6-degrees-of-freedom position tracking. One position tracker was mounted on the top rim of the shutter glasses to create images from the user's viewpoint, and the other tracker was attached to a glove worn over the dominant hand of the user to track the hand location. Motion of the hand was tracked and recorded, and the trackers were sampled at 60 Hz.

Muscle activity and user interface. The EMG data acquisition system included the 16-channel EMG transmitter unit (TeleMyo Model 2400T G2, Noraxon, Inc., Scottsdale, AZ), four EMG

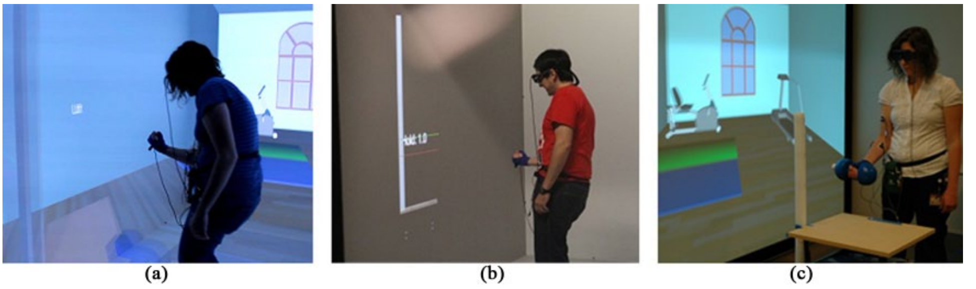

Figure 1. Panels (a) and (b) illustrate the participant performing virtual exertions inside the Cave Automatic Virtual Environment in the stereo immersive and the bland conditions, respectively; panel (c) illustrates a participant performing the equivalent task in the physical environment.

active leads with one ground lead, CF Wi-Fi radio card, PCMCIA receiver card (Cisco Aironet 802.11a/b/g wireless card bus adapter, Cisco Systems, Inc., San Jose, CA), and a data collection laptop computer with custom programmed data collection software. EMG signals were collected by the transmitter unit and then transmitted to and stored on the laptop at 3000 Hz sampling frequency. The EMG system also served as the interface between the user and the visual objects; EMG data feedback was relayed to the CAVE workstations to compare against the calibrated virtual object lifting threshold of that individual during that particular experimental session for obeying the laws of physics.

The virtual exertions muscle activity control algorithm was written in C++ and programmed in Microsoft Visual Studio (Microsoft, Redmond, WA). Data collection software interface was developed in Qt (Qt Project Hosting, Oslo, Norway). During data collection a moving root mean square (RMS) of real-time EMG with a window of 850 samples was calculated, and then the integrated RMS was sent to the CAVE workstations at 60 Hz. This integrated RMS was compared against the user-specific linear regression of biceps muscle RMS that was collected during calibration, which was the threshold value for moving the virtual object. The calibration curve illustrated in Figure 2 is representative of a typical calibration relationship between weight, height, and RMS EMG amplitude, although the exact relationship varied for each participant.

The EMG values of the biceps served as the virtual object lifting threshold since biceps were the selected prime mover in this elbow flexion

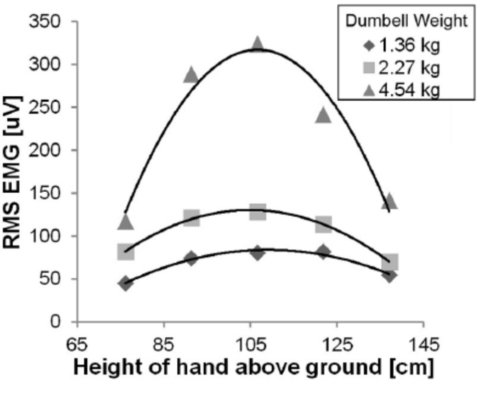

Figure 2. Typical calibration data regression curve of the biceps obtained from the experiment. All calibration curves of the biceps muscles exhibited a quadratic trend.

task. The threshold value was calculated based on the regression slope that was determined from calibration and the current tracked height of the hand (Equation 1). If the real-time EMG value was less than the threshold, the virtual object would “drop.”

$$\text{Lifting threshold value} = \text{slope} \times \text{height}^2 + \text{intercept}. \quad (1)$$

Procedure

A complete experiment consists of three sessions; each participant completed tasks in the physical, 3-D stereo, and 2-D bland conditions whereby each condition was a separate session that was at least 24 hr apart (Figure 1). The physical condition took place outside of the CAVE, and the stereo and the bland conditions were conducted in a virtual environment created inside the CAVE. A simple stereovision check was performed before the start of the experiment to verify the participants' ability in seeing stereoscopic images. They then completed a self-reported demographic questionnaire that included age, gender, ethnic background, weight, handedness, vision correction, and upper-extremity injury history. All participants were able to see stereoscopy and did not have injuries that prevented them from performing simple lifting tasks. Interpupillary distance was measured using a digital pupilometer (Digital PD ruler PM-100, Luxvision, www.luxvsion.net), and stature was measured using an anthropometric caliper. Surface EMG dual electrodes were affixed to the four muscle groups (extensor carpi radialis [ECR], flexor carpi radialis [FCR], triceps, and biceps) that were monitored using the EMG transmitter unit.

Participants were instructed to stand in the ready position before the start of any trial, which was demonstrated by the experimenter: standing upright with palms inward. The system was calibrated to participants' muscle activity profile at every session, which established the EMG threshold that was required to reach during virtual exertions. Participants then performed (a) a simple biceps curl dumbbell-lifting task and (b) a 2-min dumbbell endurance task. The rated perceived exertion (RPE) on a 0-to-10 scale (Borg, 1990) was used to assess the level of exertion after every trial during Task 1 (biceps curl dumbbell lifting) only. The NASA Task Load Index (NASA-TLX) that assessed the workload of tasks was administered at the end of every session (Hart & Staveland, 1988).

Calibration

During every session, participants lifted three physical dumbbells of known weights (1.36 kg, 2.27 kg, and 4.54 kg) to five controlled heights (76.2 cm, 91.4 cm, 106.7 cm, 121.9 cm, and 137.2 cm) and sustained holding the weight at that height for 5 s. They were instructed to keep the upper arm parallel to their torso and only flex at the elbow. The dumbbells were standard weights and the heights were selected to span the flexion and extension range of the elbow joint. EMG was recorded during the 5-s isometric contraction, and then the integrated biceps RMS EMG was calculated to determine the regression equation. The integrated biceps RMS EMG magnitude served as the action threshold that the participants were required to produce and to maintain in order to achieve a successful "lift" in the 3-D stereo and 2-D bland conditions. After each dumbbell-lifting calibration trial, a 30-s rest break was provided.

Additionally, three elbow flexor maximum voluntary contractions (MVCs) were performed at heights of 91.4 cm, 106.7 cm, and 121.9 cm during every session. Elbow flexor MVCs were performed by pulling against a handle that was connected to an adjustable metal chain, which was affixed to a solid board on which the participants stood. The associated RMS EMG values from an angle-specific maximal isometric voluntary contraction were selected to be the normalization reference values in this study, which was similar to Burden (2010), who used the peak EMG from a maximal isometric voluntary contraction for the same muscle and joint angle for normalization. Extended rest breaks of 3 min were provided after each MVC trial.

Tasks

Biceps curl dumbbell-lifting task. Participants lifted three objects of identical appearance but of varying weights (1.36 kg, 2.27 kg, and 4.54 kg) to three controlled heights (91.4 cm, 106.7 cm, and 121.9 cm). For the physical condition, the physical dumbbells were customized hollow dumbbell containers that were filled with lead shot to measured weights. Photographs of the customized physical dumbbells were taken to create the graphics for the virtual dumbbells used in the stereo condition. For the bland condition with minimal immersion, the dumbbell visuals were replaced with a single line that represented minimal graphics.

At the initiation of a physical trial, the experimenter placed a physical dumbbell on a table in front of the participant; for the virtual trial, the computer rendered a virtual dumbbell in the stereo condition or a line in the bland condition on a virtual table in front of the participant. For all conditions, participants first assumed the ready position, and then a synthetic verbal cue announced, "Please grasp and lift the weight up to the instructed height using sufficient effort to overcome the load, but without over exerting or becoming fatigued." In the physical condition, the experimenter verbally announced one of the heights that were marked on a stick, and in the virtual conditions, the computer rendered the appropriate label on a stick, and then the participant lifted the object and sustained at that height for 5 s. In the physical environment, the experimenter counted down 5 s and then instructed the participant to "please return the weight to the table and then relax." All heights were randomized.

The criterion for holding virtual objects in the hand is based on the real-time biceps EMG RMS magnitude while the position is tracked. When the real-time biceps EMG was at least equal to or greater than the calibrated EMG threshold, the virtual object was displaced relative to the hand motion. At the initiation of a trial, the word *Lift* appeared on the CAVE wall in front of the participant. The virtual object was superimposed in the tracked hand, so when participants performed a biceps curl and they were at or above the threshold, the virtual object appeared to move along with the hand. If the real-time EMG fell below the threshold, the object would instantaneously return to the table and the word *Dropped* would appear on the CAVE wall, and then the participant would have to lift the dumbbell from the table again. The threshold was weight and height specific; trials that involved heavier virtual objects had greater thresholds that varied across the range of elbow flexion positions. After successfully sustaining the virtual load at the given height for 5 s in the CAVE, a synthetic verbal cue announced, "Please return the weight to the table and then relax." Thirty-second rest breaks were provided between each trial, and there was a rest break of at least 5 min at the end of biceps curls trials.

Two-minute endurance task. After the completion of the biceps curl dumbbell-lifting task, the participants were instructed to grasp, lift, and hold a 4.54-kg dumbbell at 90° elbow flexion and to sustain it for 2 min. In the physical condition, the experimenter reminded the participant at 1 min and then 10 s before reaching 2 min. In the virtual conditions, a countdown timer appeared on the CAVE wall in front of the user that indicated the time. Participants rated their level of fatigue after the endurance task with the following instruction: "With 0 being *not fatigued*, and 10 being *the most fatiguing situation you've experienced*, how would you rate your level of fatigue right now? Fatigue feels like discomfort, a slight burning sensation, or pain in the muscles."

Experimental Design, Variables, and Data Analysis

Participants completed a total of 27 biceps curl trials (three replications for the three weights at three different heights) per session. They performed one endurance task per session after the biceps curl task and then completed the NASA-TLX at the end of each session.

Independent variables were virtual environment condition (three levels), weight (three levels), and height (three levels). Dependent variables were EMG of the four muscle groups, RPE, and NASA-TLX. Mean power frequency (MPF) from the initial and final 10 s of the endurance task was extracted to analyze muscle fatigue.

All EMG data were normalized against the level of contraction of the muscles recruited during an elbow flexion MVC at each height for a specific session. Since the normalization MVCs were performed only for elbow flexion, only the normalized biceps EMG values were tested for the effects of condition, weight, and height using repeated-measures ANOVA, and then post hoc pairwise comparisons were conducted to examine the differences between conditions with Holm-Bonferroni alpha correction for the biceps. Normalized triceps, FCR, and ECR were tested only for the effect of weight and height within the same condition. Biceps MPF was tested for the effect of condition and endurance time; the MPF of triceps, FCR, and ECR were tested only for the effect of endurance time within the same condition. The significance level was at .05 for all tests.

RESULTS

Biceps Curl Task EMG

Biceps. The two-way and three-way interactions were not statistically significant. There was a significant main effect of condition for the biceps, $F(2, 8.65) = 10.74$, $p = .005$ (Figure 3). Statistically controlling for weight and height at

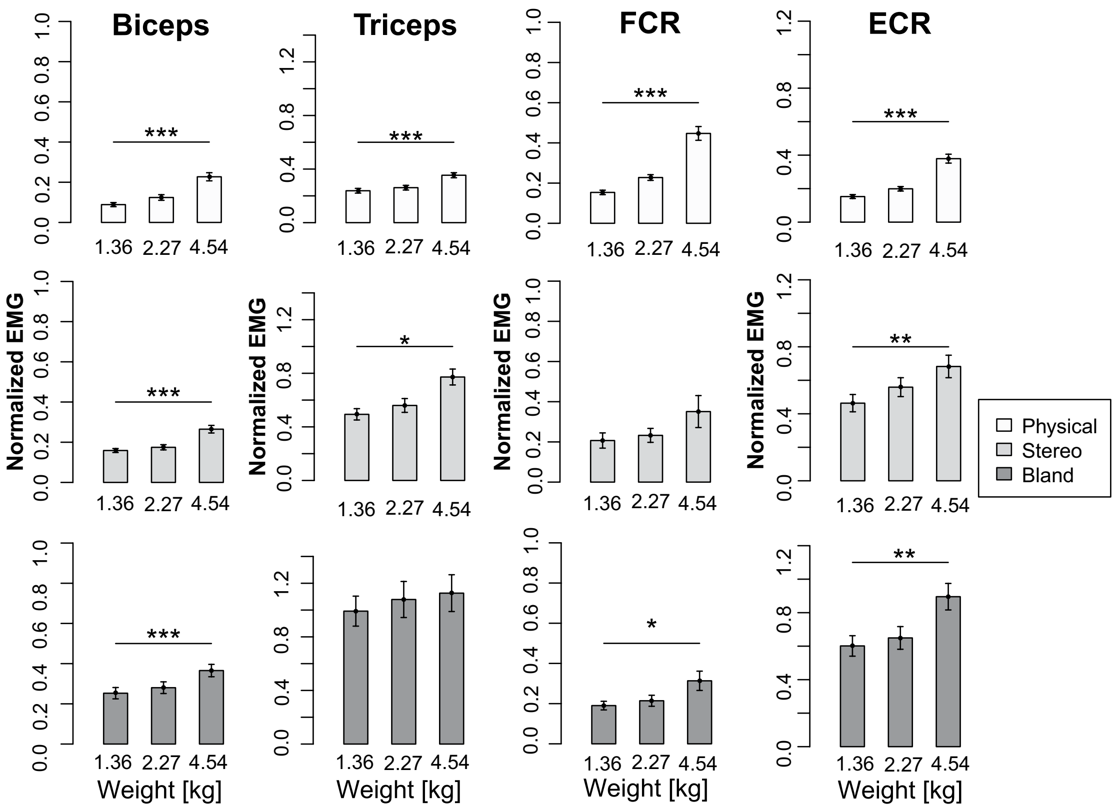

Figure 3. Normalized biceps, triceps, flexor carpi radialis, and extensor carpi radialis activities are plotted by weight for the physical, stereo, and bland conditions (±1 *SE*; *$p < .05$, **$p < .01$, and ***$p < .001$). The unit on the vertical axis is normalized EMG activity.

their means, we found pairwise comparison revealed that EMG activity in the physical condition was 0.158, $F(1, 9.15) = 16.86$, $p = .005$, and 0.053, $F(1, 10) = 7.09$, $p = .024$, normalized units less than in the bland and stereo conditions, respectively. On average, weight significantly affected biceps activities, $F(1, 9.97) = 76.67$, $p < .001$), but there was no effect of height.

Triceps, FCR, and ECR. Overall, activities of these three muscles increased as the weight of the object increased. Weight significantly affected the triceps for the physical, $F(1, 10) = 45.97$, $p < .001$, and stereo conditions, $F(1, 10) = 17.50$, $p = .002$. FCR was also affected by weight for the physical, $F(1, 10) = 50.48$, $p < .001$, and bland, $F(1, 9) = 9.67$, $p = .013$, conditions. In ECR, the effect of weight was significant in the physical, $F(1, 10) = 67.40$, $p < .001$; stereo, $F(1, 9) = 19.91$, $p = .002$; and bland, $F(1, 10) = 12.64$, $p = .005$, conditions. There was no effect of height on EMG level.

Perceived Exertions

The RPE was analyzed using a 3 (condition) × 3 (weight) × 3 (height) mixed-effects repeated-measures ANOVA. There was a two-way interaction between weight and condition, $F(2, 8.86) = 16.23$, $p < .001$. For every 1-kg increase in weight, RPE increased 1.385 units, $F(1, 10) = 83.10$, $p < .001$, in the physical condition; increased 0.636 units, $F(1, 10) = 21.49$, $p < .001$, in the stereo condition; and increased 0.350 units, $F(1, 9.84) = 5.13$, $p = .047$, in the bland condition (Figure 4). There was a significant effect of weight, $F(1, 10) = 97.66$, $p < .001$, and there was no significance for condition or height ($p > .05$).

EMG MPF

Biceps. The two-way interaction between condition and endurance time was not statistically significant. There was a significant main effect of

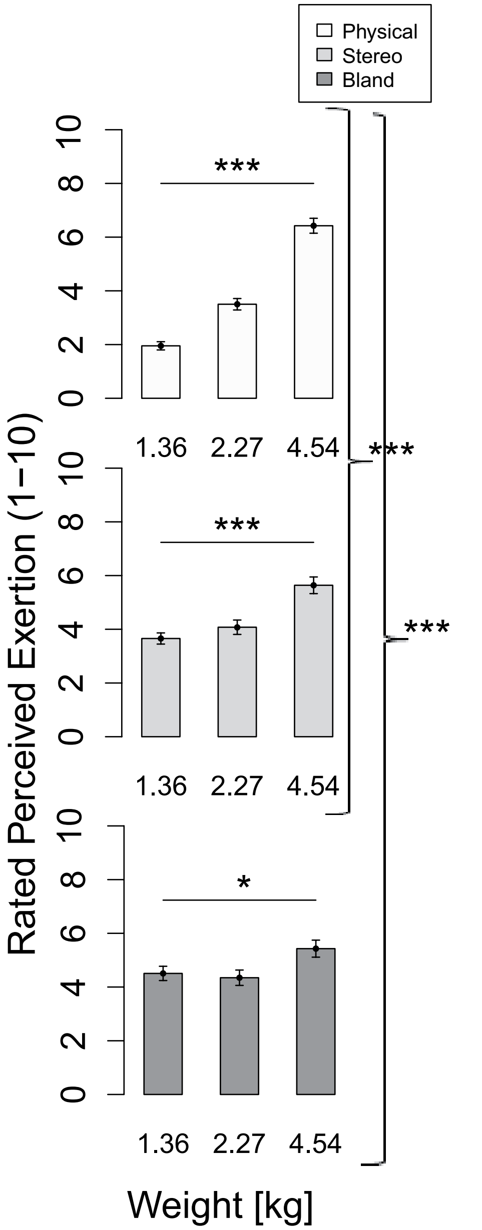

Figure 4. Perceived exertion in terms of rated perceived exertion (0-to-10 scale) by weight for the physical, stereo, and bland conditions (±1 *SE*; **p* < .05, ***p* < .01, and ****p* < .001). Interaction between condition and weight are denoted by curly braces, indicating the rate of change in weight in the physical condition was statistically significantly different from the rate of change in weight in the stereo and the bland conditions.

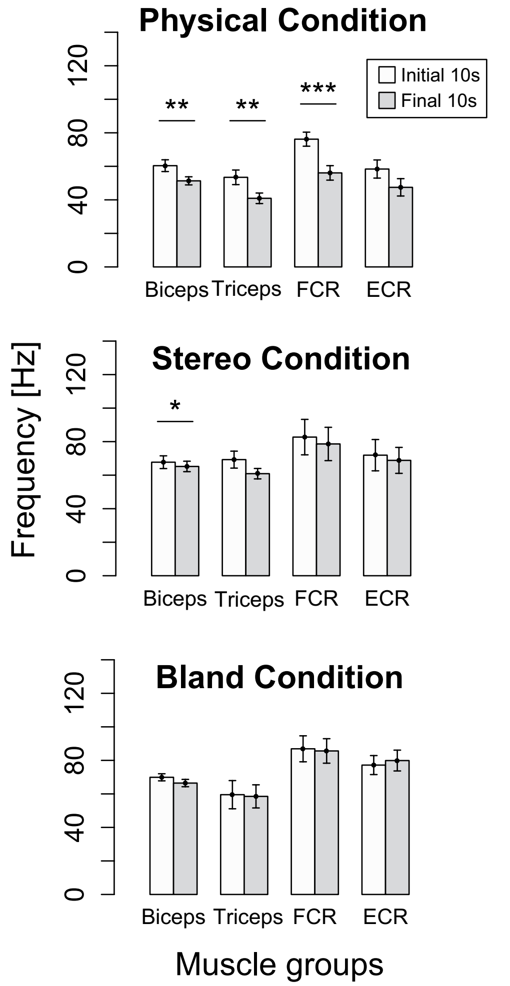

Figure 5. Mean power frequency (Hz) by muscle groups over time for physical, stereo, and bland conditions (±1 *SE*; **p* < .05, ***p* < .01, and ****p* < .001).

condition for the biceps MPF, $F(2, 8.53) = 5.66$, $p = .027$. On average, the physical condition had the lowest MPF; pairwise comparison indicated that the physical condition was 12.24 Hz, $F(1, 9.91) = 12.38$, $p = .006$, and 10.93 Hz, $F(1, 9.87) = 5.87$, $p = .036$, lower than the bland and stereo conditions, respectively (Figure 5). There was 5.07 Hz decrease shift in MPF, $F(1, 9.91) = 12.71$, $p = .005$, over the course of 2 min.

Triceps, FCR, and ECR. Over the course of 2 min, a significant decrease shift of MPF was observed for the physical condition; a decrease of 12.52 Hz was observed for the triceps, $t(10) = 4.52$, $p = .011$; 20.11 Hz for the FCR, $t(10) = 5.14$, $p < .001$; and 10.92 Hz for the ECR, $t(10) = 5.30$, $p < .001$. No significant decrease shift in the bland or stereo conditions was observed.

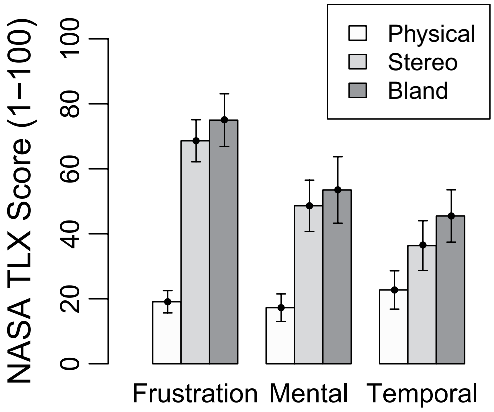

Figure 6. Raw scores (range from 0 to 100) of three subscales of NASA Task Load Index (Frustration, Mental Demand, and Temporal) across the three conditions (±1 *SE*). Within the same subscale, pairwise comparisons indicated statistically significant difference between conditions, with physical condition as the reference level (*$p < .05$, **$p < .01$, and ***$p < .001$).

NASA-TLX

One-way repeated-measures ANOVA was used to compare NASA-TLX (overall and subscale scores) among all conditions (three levels). Significant effect of condition was observed in Frustration, $F(2, 8.67) = 32.63$, $p < .001$; Mental Demand, $F(2, 8.60) = 5.78$, $p = .026$; and Temporal, $F(2, 8.70) = 4.51$, $p = .045$, subscales. In general, overall score, effort, performance, and physical demand were not affected by condition. With the physical condition as the reference level, further pairwise comparison results of the three statistically significant subscale scores are illustrated in Figure 6.

DISCUSSION

This study was a proof of concept for the method of virtual exertions, and it demonstrated that users were able to successfully manipulate virtual objects in the hands and simulate forceful exertions through the use of body movement tracking and EMG. The novelty of virtual exertions is that we involve the same muscle group co-contractions used for that activity in the physical environment as the interface with the virtual objects. It enables users to perform exertions when interacting with virtual objects as with physical objects, without manipulating or grasping supplemental control inputs or physical items to interact with virtual objects. Virtual exertions offer inherent haptic feedback through the proprioceptors and muscle stretch and tension receptors involved in the exertions and may provide a flexible method of simulating physically demanding activities in VR as users are not bound to a fixed location due to stationary or bulky interfacing and feedback devices. Virtual exertions may prove important for safely simulating physically demanding activities, rehabilitating patients from stroke and injuries, and understanding how to make safer environments and workplaces, but the potential of virtual exertions has yet to be exploited.

In this study, we created three environmental conditions for studying human performance, which included a physical condition that involved lifting dumbbells in the physical environment, a 3-D stereo condition with stereoscopic visuals of virtual dumbbells in the virtual environment, and a 2-D less-immersive bland condition with minimal 2-D visuals in the virtual environment. We examined EMG values that were normalized against each muscle's respective reference values collected during an elbow flexion MVC, which was the same posture as the experimental task. Since the MVC normalization was performed only for elbow flexion in order to avoid fatiguing the participants, only the biceps EMG would be considered normalized. Although it might be expected that the observed triceps, FCR, and ECR were representative of their associated recruitment levels during an elbow flexion MVC, there were no assurances that recruitment for these muscles was consistent from session to session, and therefore only the biceps EMG was compared across conditions.

When participants sustained and held the virtual object in the task posture, they co-contracted the agonistic and antagonistic muscles against projections of virtual objects in the two virtual conditions, and the trend of the biceps EMG and perceptions of virtual loads corresponded to lifting the dumbbells in the physical condition. Participant physiological responses in terms of EMG recordings indicated increased muscle activity with increased object weight and fatigue patterns, which was a common trend mostly within the physical and stereo conditions. Although the EMG recording indicated greater biceps activity in the virtual conditions, no statistically significant effects were observed for RPE that were solely related to condition.

One major difference between the physical and virtual tasks was the absence of physical reaction forces, or gravity, for the virtual conditions. Visual feedback and biofeedback in suggesting weights of virtual objects may have enhanced user experience, as it might have helped evoke the experience of physical exertion in VR and in turn helped provide a simulation that better represented the characteristics of the physical world. In this study, we controlled the weight of a virtual object through the calibration procedure for each participant, by mapping muscle activity to the corresponding activity generated for the physical weight. EMG activity of the two pairs of agonist-antagonist muscles, the biceps–triceps and the FCR–ECR, increased as the weight of the dumbbells increased for the physical and the two virtual conditions.

Previous studies have incorporated force simulation in VR via various modes of user feedback. One way to simulate object weight and gravity is by incorporating physical kinematics in the VR simulation. Users touched physical objects and the movement of the physical object was tracked by sensors and in return controlled the movement of the same virtual object seen in a head-mounted display (Hoffman, 1998). The need of having physical objects limited the simulation to have physical objects for all interactive items, and users could not precisely see their own body and hands, which is critically important for performing dexterous activities. Alternatively, force feedback was provided through touch feedback devices, such as the PHANToM or the Cyberglove (Burdea et al., 2000; Popescu et al., 2000; Sallnäs et al., 2000). These devices, too, sometimes limited the ability to simulate a full, functional range-of-motion movement. Correspondingly, a pneumatic skeletal glove may impede movements and the direct interaction with virtual objects.

The biceps were the selected prime mover in this study because both tasks involved elbow flexion, whereas other elbow flexors, including the brachialis, were not included for simplicity. Although biceps activity in the virtual exertions simulation exhibited the same patterns in response to the weight of the objects for the two virtual and physical conditions, the biceps EMG was significantly greater for the two virtual conditions than for the physical condition. It is probable that the lifting threshold imposed a limitation to the muscles and force production, which resulted in the increased recruitment of muscle fibers (De Rugy, Loeb, & Carroll, 2012). Since the EMG control algorithm for the virtual conditions was based on biceps muscle activity for the corresponding physical task, the biceps activity was the threshold for exertions against the VR object.

If the normalization reference values for the triceps were representative of their recruitment between conditions, the control algorithm may have produced triceps co-contractions that were much greater than the antagonistic muscle compensation observed in the physical condition. This effect was biomechanically plausible 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 physical task. In some cases, triceps contraction in the two virtual conditions exceeded the reference level obtained from the calibration, perhaps due to different muscle recruitment (Figure 3) for the co-contraction exertions in substitution. Furthermore, in order for the flexors to reach the same level of muscle activity given an exertion and a posture (e.g., biceps curl), the co-contracting extensors served as the "load" that the flexors worked against during virtual exertions. The extensors co-contracted excessively in VR to counter the torque produced by the flexors. Performing virtual exertions might also accelerate the arm faster before activation of the antagonist due to the lack of a physical weight. Moreover, as suggested by De Luca and Mambrito (1987), co-contraction is present when individuals are uncertain about the task or need compensatory force for the task, which both may be the case for novel users of virtual exertions.

To mitigate the excessive exertion of the antagonist muscles, in future studies we plan to proportionally lower the threshold of the prime mover in a particular virtual task (e.g., in a lifting task) so that users of virtual exertions will not need to overexert the antagonist. In other words, we would programmatically balance the required EMG threshold of the prime movers against the necessary torque produced by the antagonist to counter the torque produced by the agonist for joint stabilization. Additionally, MVC exertions would be performed for all muscles involved in doing the task for EMG normalization. This method could lead to more comparable overall muscle activity levels between physical and virtual environments for the same task and is the topic of future work.

Further examination of biceps activity using pairwise comparisons revealed that the difference in muscle activity between the physical and the bland conditions was generally greater than the difference between the physical and the stereo conditions. The main difference between the two virtual conditions was that the stereo condition had greater correspondence and visual match to the physical condition than did the bland condition. Consequently, the stereo condition was more immersive (Slater, Usoh, & Steed, 1995) than the bland condition. Previous studies have suggested positive effects of immersion on user learning performance (Gutiérrez et al., 2007; Patel, Bailenson, Hack-Jung, Diankov, & Bajcsy, 2006) and user performance measured in terms of accuracy (Narayan, Waugh, Zhang, Bafna, & Bowman, 2005) in a virtual environment. The findings of the current study support the previous literature that user performance and responses in the more immersive simulation better corresponded to the physical condition.

Muscle fatigue over time was also observed, which was suggested by a decreasing shift in MPF during the endurance task (Figure 5). The shift in MPF was observed for all four muscle groups in the physical conditions, and in the stereo condition, only the biceps revealed a decreasing shift. This occurrence could be explained by the threshold parameter of the control algorithm. In this experiment, the participant's biceps activity was the only determinant in the EMG threshold for moving the virtual objects, which may lead to fatigue of just the biceps. Some participants experienced "drops" of the objects in the virtual conditions throughout the endurance task due to insufficient muscle activity. In the process of retrieving the dropped virtual dumbbells, the participants may have recovered somewhat from the endurance task. It is also probable that this measure of fatigue is not very indicative in the two virtual conditions, compared to the physical condition.

The psychophysical measure, RPE, was significantly affected by weight. The participants perceived increased effort required for lifting heavier weights under all VR conditions. A statistical interaction between weight and condition for RPE was also observed, which revealed that perceived effort by weight was related to condition. For instance, on average, the participants indicated a 1.385 increase in RPE for a 1-kg increase in weight in the physical condition, yet they indicated only a 0.350 increase in RPE for a 1-kg increase in weight in the 2-D bland condition. This finding suggested greater rate of perceived effort increase when the weight of the dumbbell increased in the physical condition than in the bland condition. Moreover, the participants perceived only a practically small difference in the amount of effort needed to move objects across the three environments, particularly between the physical and 3-D stereo VR conditions. Despite the notable significant differences in the biomechanical and physiological responses of the biceps and greater antagonist activity, the same RPE trends in response to weight in the three conditions suggest that users were able to suspend belief while performing suggested exertions in the virtual environment. How these physiological response differences might actually alter behavior in a more complex simulation, or be constrained, is the topic of future study.

It is also worth noting that the physiological response differences between the physical and bland conditions observed in biceps EMG magnitudes were greater than the differences between the physical and stereo conditions, although this finding was not reflected in the RPE. A possibility is that given a lack of familiar visual cues (i.e., the objects did not appear in the hands for the bland condition), participants approached lifting tasks more forcefully out of uncertainty. It is also possible that the bland condition influenced the participants to exert differently and less efficiently. Yet, it seems surprising that the extra muscle activity was not "felt" by the participants. In some ways, this finding brings into question the meaning of subjective assessments for virtual tasks. For each condition, the participant was given the same task and subjectively believed he or she had acted the same way, but the difference was observed in the subconscious muscle activations. The extent of the effect of visual cues on biomechanics was not the emphasis of this study but may be investigated in future experiments.

Moreover, the participants responded that mental demand, frustration, and temporal demand (i.e., time pressure) for the virtual conditions were greater ($p < .05$) than for the physical condition, as indicated by the NASA-TLX subscale scores. These results suggest that the participants expended more cognition when performing the task in the virtual conditions, and unsuccessful lifts (e.g., dropping the virtual weight) led to frustration and not being able to perform the task properly. However, overall workload, effort, performance, and physical demand were not significantly affected by condition. These findings coincide with the RPE scores, as the participants did not subjectively believe that the efforts were different among conditions. Overall, the virtual conditions imposed a greater workload on the participants.

Controlled heights were not participant corrected in this study in order to observe how varied attributes (i.e., participant size) affect performance, as is the case when simulating actual tasks in VR. The EMG calibration curves for varying heights may have been affected by the force–length relationship observed in typical isometric contractions, or possibly, muscle sliding under the skin resulted in fewer EMG signals being detected by the surface electrodes. In this experiment, the participants calibrated the system by lifting known weights to several controlled discrete heights above the ground. When the participants lifted the weight to the lowest and the highest locations, muscle activity was relatively less than the muscle activity when they lifted the weight to the medium height (Figure 2).

Participants mentioned the unnatural "drops" of virtual weights falling out of their hands as soon as the EMG threshold was not met. The EMG control algorithm could be improved so that the virtual weight may gradually lower and move away from the hands to indicate that the threshold is not met. The current study was limited to biceps EMG comparisons across different virtual environment conditions because the reference value used in EMG normalization was obtained for elbow flexion MVCs from each session. To allow comparisons of all muscles across conditions, MVCs for all muscles should be performed during all sessions. Alternatively, though less feasible due to participant fatigue, is to conduct all experimental conditions on the same day. Another EMG control algorithm improvement would be establishing an EMG threshold that evokes more appropriate exertions in the co-contraction muscle pairs when lifting virtual objects (e.g., producing EMG signals that are not statistically significantly different between physical and virtual environments). Also, the visuals and animations of the virtual objects are another area for improvement. Another interesting variable to study is time to fatigue, which was not examined in the current study. This variable may provide more insights regarding how long individuals will be able to perform tasks or undergo training in the virtual environment. The use of virtual exertions for cognitively demanding tasks should be evaluated because the users of this system have indicated high mental demand when performing virtual exertions.

We anticipate numerous benefits from using the virtual exertions approach for evoking the sense of physical exertions in VR using a CAVE. Virtual exertions do not depend on physical items and objects, which may be impractical to use inside a CAVE because one cannot drop physical objects in a fragile CAVE. Also, objects that the users interact with can be located anywhere in the virtual environment, such as on tables or behind doors or obstacles, which would not be possible otherwise. These objects can be easily programmatically varied in size and loading characteristics for a more flexible simulation than physical simulations. It does not involve bulky apparatus or external objects (light surface electrodes only) for force reflection or haptic feedback equipment in suggesting muscle contraction. Users use the same postures and muscle groups that are used in the physical task during virtual exertions rather than operating wands (i.e., remote control of the CAVE) and hand-operated controls for doing physical tasks.

Virtual exertions may provide an alternative and an evocative method to interact with virtual objects. Instead of interfacing with the virtual objects with a controller or involving physical items, users were able to maneuver virtual objects directly through their tracked hand positions and muscle contractions. Virtual objects could be flexibly programmed into the VR environment at any given location in space, and users of virtual exertions could use the posture that they would normally pose in the physical environment to grasp or lift a virtual object. A virtual exertion does not necessarily need to recreate the experience of the physical activity; it merely needs to provoke the participant in eliciting muscle co-contractions and positioning himself or herself the way that he or she would behave in the physical situation such that a mapping will be possible. Demonstrating the feasibility to control and interact with virtual objects through muscle activity provides the opportunity to conduct simulations that involve both cognitive and physical demands simultaneously; users will be able to perform physical tasks and interface with the virtual objects through direct interactions and then allocate their attention for the more mentally demanding portion of the task. For instance, attention allocation and cognitive loading in a first respondents rescue training task take precedence over performing exertions.

CONCLUSIONS

Virtual exertions are the mapping of quasi-static co-contractions and forceful actions for simulating exertions against objects using projections of objects in the hands as an interface with the virtual environment. Virtual exertions do not aim to replicate the exact exertions of people in the physical environment, and it was observed that the participants did produce more effort than they necessarily needed for a physical exertion. Our findings reveal, however, that virtual exertions are evocative of physical exertions and do have similarities to physical exertions in the prime mover of the task. The trend of increase in all muscle activity in response to increasing load weight was observed in the physical and the two virtual conditions, and the trend of decrease in shift in EMG MPF for the biceps had the same fatigue patterns over time. Although the overall biceps activity and workload were greater in the virtual conditions, the subjective perceived effort of the users was not statistically significantly different among the conditions. These results revealed that virtual exertions might help contribute to better training as well as provide a safer way for conducting laboratory studies in human factors and ergonomics. Finally, we anticipate that virtual exertions may be useful for physical training and rehabilitation and still achieve comparable levels of physical activity.

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KEY POINTS

- Muscle activity level and subjective effort rating were affected by the load weight in the physical and virtual environments, and the trends for all environments were the same.
- Trends in ratings of perceived effort in response to weight were the same across physical and virtual environment conditions, with small differences between the physical and stereo virtual reality conditions.
- Participants indicated greater cognitive load in the virtual environment conditions.
- The muscle activity in the more immersive stereo environment differed less from the physical condition than the bland condition.

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