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A training platform for many-dimensional prosthetic devices using a virtual reality environment

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HIGHLIGHTS

- A virtual upper limb prosthesis with 27 anatomically defined dimensions is deployed as an avatar in virtual reality.
- The prosthesis avatar accepts kinematic control inputs and neural control inputs.
- Performance under kinematic control is achieved by two non-human primates using the prosthesis avatar to perform reaching and grasping tasks.
- This is the first virtual prosthetic device that is capable of emulating all the anatomical movements of a healthy upper limb in real-time.
- This is customizable training platform for the acquisition of many-dimensional neural prosthetic control.

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ABSTRACT

Brain machine interfaces (BMIs) have the potential to assist in the rehabilitation of millions of patients worldwide. Despite recent advancements in BMI technology for the restoration of lost motor function, a training environment to restore full control of the anatomical segments of an upper limb extremity has not yet been presented. Here, we develop a virtual upper limb prosthesis with 27 independent dimensions, the anatomical dimensions of the human arm and hand, and deploy the virtual prosthesis as an avatar in a virtual reality environment (VRE) that can be controlled in real-time. The prosthesis avatar accepts kinematic control inputs that can be captured from movements of the arm and hand as well as neural control inputs derived from processed neural signals. We characterize the system performance under kinematic control using a commercially available motion capture system. We also present the performance under kinematic control achieved by two non-human primates (*Macaca Mulatta*) trained to use the prosthetic avatar to perform reaching and grasping tasks. This is the first virtual prosthetic device that is capable of emulating all the anatomical movements of a healthy upper limb in real-time. Since the system accepts both neural and kinematic inputs for a variety of many-dimensional skeletons, we propose it provides a customizable training platform for the acquisition of many-dimensional neural prosthetic control.

1. Introduction

Millions of people worldwide suffer from intractable medical conditions that result in permanent motor disability (Lebedev et al., 2011). Brain machine interfaces (BMIs) are devices that use recorded neural activity to control external actuators, and have the potential to restore lost function to patients suffering from a variety of motor disorders (Donoghue, 2002; Hatsopoulos and Donoghue, 2009). BMIs that seek to perform arm and hand functions are difficult to design, however, as many dimensions must be under simultaneous control by the patient (Carmena et al., 2003; O'Doherty et al., 2011). Consequently, it is important to develop an environment that can support the training of many-dimensional (many-D) neural prosthetic control.

An exclusive emphasis on robotic devices for many-D BMI control hinders progress for several reasons. Manufacturing many-D prosthetic devices for musculoskeletal rehabilitation is expensive because of the costs associated with fabrication of multiple iterations of these devices (Davoodi and Loeb, 2011). More importantly, current state-of-the-art robotic devices are not yet capable of real-time high dimensional, natural movements that allow users to embody the prosthetic device. Such differences will not allow

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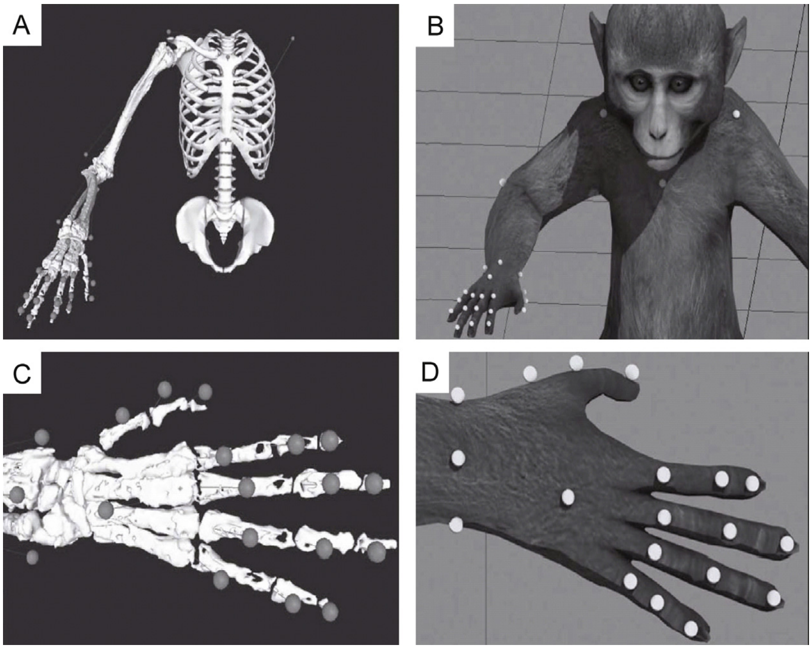

Fig. 1. The motion capture system tracks the location of 24 retro-reflective markers that extend from the shoulders to the tips of the fingers. Marker location is determined by proximity to specific bony landmarks (A) that will provide the most accurate information related to joint position, and are then adhered to the skin immediately above these landmarks (B). Successful tracking of this marker-set allows for accurate joint information to be solved across the 20 upper limb joints and 27 specific joint movements (Table 1).

systematic testing of how these variables may affect neural responses and control of a prosthetic. Virtual devices offer a safe and practical alternative to manufactured robotic devices. Effective control requires many hours of practice in a safe, behaviorally relevant environment which can be achieved through the effective use of virtual reality environments (VREs, Bohil et al., 2011). Major technological developments in recent years have made it possible for VREs to be highly immersive environments, where a multitude of behaviors can be learned and trained (Bohil et al., 2011). Previously, VREs have been shown to be effective rehabilitative tools for retraining motor function following stroke (Jack et al., 2001; Holden et al., 2005; Kuttuva et al., 2005, 2006; Piron et al., 2009; Burdea et al., 2011), treating phantom limb pain conditions in amputees (Murray et al., 2006; Cole et al., 2009; Alphonso et al., 2012) and designing and simulating the use of expensive prosthetic devices prior to fabrication (Soares et al., 2003; Sebelius et al., 2006). This means the development of VRE-based prosthetic training environments offers important new opportunities.

Low-D BMI systems, such as those involving a cursor in Cartesian space (2- or 3-D) and an oriented gripper (4-D to 7-D), have previously been employed in VREs and VREs appear to be a potentially valuable tool (Hauschild et al., 2007; Marathe et al., 2008; Aggarwal et al., 2011; Resnik et al., 2011; Davoodi and Loeb, 2012; Kaliki et al., 2013). However, for a VRE-based BMI training system to be truly effective, it must include a way to make quantitative measures to evaluate user performance in a 3-D environment (Marathe et al., 2008; Resnik et al., 2011), and have real-time capabilities (Schalk et al., 2004; Wilson et al., 2010). Further, for this system to be a viable option for mainstream use, there must be a demonstration of diverse functionality and a software framework that is accessible to as many potential users as possible (Mason and Birch, 2003; Schalk et al., 2004; Brunner et al., 2011).

Despite these advantages, a virtual prosthesis that can emulate all of the dimensions necessary for full control of a human upper limb in real-time is not currently available. Further, upper limb virtual prostheses that currently exist do not have design characteristics that are conducive to a generalized BMI system framework (Bishop et al., 2008), nor do they provide a framework for quantitative assessment of task performance in a 3D environment (Resnik et al., 2011). Here, we discuss a novel method for the development of a virtual, upper limb prosthesis capable of giving the user independent control of 27-D in real-time and then assess the performance metrics of non-human primates using the limb to perform tasks in a 3-D VRE.

2. Methods

2.1. Animal preparation

Two non-human primates (*Macaca mulatta*) were used for these experiments. All surgical and animal care procedures were approved by the New York University Animal Care and Use Committee and were performed in accordance with National Institutes of Health guidelines for care and use of laboratory animals.

2.2. Motion capture

We used motion capture to allow the virtual prosthesis to be used under kinematic control.

Twenty-four spherical, retro-reflective markers were non-invasively adhered to sites on the upper torso, and multiple bony landmarks on the right upper limb of each subject (Fig. 1A). We used markers whose sizes ranged in diameter from 7 mm (markers on the sternum, shoulders and right elbow; Fig. 1B) to 2 mm (markers on the digits; Fig. 1B). Markers were placed at locations on the upper body to permit the calculation of kinematic information across 27 dimensions, which covers all of the physiological movements of the 19 joints of the upper limb (Table 1). All movements that the animals made inside a rig were captured using 26 infrared (735 nm) and near-infrared (890 nm) cameras capable of motion capture at frame-rates of up to 245 Hz (Osprey Digital Real Time System, Motion Analysis Corp., Santa Rosa, CA). Note that motion capture was needed only when the virtual prosthesis was used under kinematic control. Cameras were placed to permit marker