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Development of a closed-loop feedback system for real-time control of a high-dimensional Brain Machine Interface

David Putrino, Yan T. Wong, *Member, IEEE*, Mariana Vigeral, and Bijan Pesaran, *Member, IEEE*

Abstract— **As the field of neural prosthetics advances, Brain Machine Interface (BMI) design requires the development of virtual prostheses that allow decoding algorithms to be tested for efficacy in a time- and cost-efficient manner. Using an x-ray and MRI-guided skeletal reconstruction, and a graphic artist's rendering of an anatomically correct macaque upper limb, we created a virtual avatar capable of independent movement across 27 degrees-of-freedom (DOF). Using a custom software interface, we animated the avatar's movements in real-time using kinematic data acquired from awake, behaving macaque subjects using a 16 camera motion capture system. Using this system, we demonstrate real-time, closed-loop control of up to 27 DOFs in a virtual prosthetic device. Thus, we describe a practical method of testing the efficacy of high-complexity BMI decoding algorithms without the expense of fabricating a physical prosthetic.**

I. INTRODUCTION

Brain Machine Interface is a developing technology that has the potential to assist in the treatment of multiple disorders where limb use is compromised, and unable to be restored with currently available rehabilitation techniques [1]. Given the dominant role of the upper limb in functional independence, providing patient access to BMIs that can accurately replicate upper limb function is a priority. Upper limb BMI development depends upon the simultaneous and accurate measurement of a number of different factors such as joint kinematics, neural activity and task-related parameters [1-3]. In humans, the upper limb has a potential for functional diversity that requires independent control across multiple DOFs, with estimates ranging from 7 DOFs for control of simple target pointing in a basic upper limb model [4], to 30 DOFs for a sophisticated wrist-hand complex [5].

Uncertainty about how the independent control of many DOF is necessary for the functional diversity of the upper limb means prosthetic design and fabrication is both a difficult and expensive process. One potentially effective strategy for optimizing prosthetic design without the complications associated with fabrication is the use of high-quality, anatomically accurate virtual prostheses [6]. Anatomically accurate virtual prostheses were first developed for patients with unilateral upper limb amputations using a DataGlove on the unaffected limb [7], and this paradigm has since been expanded to 18 DOFs using differing methodologies [8,9]. Musculoskeletal modeling software (MSMS), a virtual rendering tool, is used by a number of groups to achieve the goal of high-DOF virtual prostheses [6, 9-13]. However, this approach suffers from calculation lags, which prevent its use in real-time, closed-loop systems that utilize high DOF virtual prosthetics. The goal of the present study is to introduce methodology that can be used to monitor upper limb kinematics across 27 DOFs on a virtual upper limb avatar in a closed loop environment in real-time.

II. ACQUIRING KINEMATIC DATA

Two non-human primates (*Macaca Mulatta*) were trained to perform a number of reaching, grasping and manipulation tasks in a three dimensional space, involving one freely moving upper limb while the other limb was restrained. 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. A schematic of the experimental environment, and the items that the animals were trained to grasp are detailed in Figs. 1A and B, respectively. The experimental animals were trained to tolerate spherical motion capture markers non-invasively adhered to sites on their upper torso, and multiple bony landmarks on the right upper limb (24 markers in total), which ranged in diameter from 2 mm (markers on the digits; Fig. 1C) to 7 mm (markers on the upper torso).

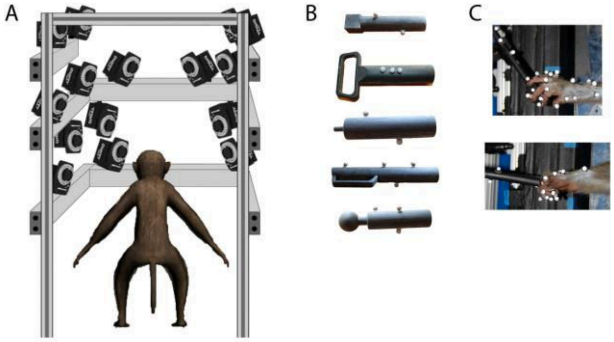

Figure 1. A schematic of the rig setup with motion capture cameras (A), photographs of the different shapes that the animals were trained to grasp (B), and photographs of an animal's hand with a markerset attached as it grasps one of the objects (C).

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Y. W., M.V. D.P., and B. P. are with the Center for Neural Science, New York University USA

Corresponding author: Bijan Pesaran: phone: 212-998-3578; fax: 212-995-4011; e-mail: bijan@nyu.edu).

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These markers were specifically located on the upper body to permit the calculation of precise kinematic information across 27 DOFs related to movements of 19 joints (Table 1). Task performance was captured at a frame-rate of 200 Hz using a motion capture system made up of 16 infrared and near-infrared cameras (Osprey Digital RealTime System, Motion Analysis Corp., USA), and data related to marker location was streamed into Cortex (Santa Rosa, CA), a specialized motion capture software platform developed by Motion Analysis Corp. Accuracy of marker localization depends heavily on the accuracy of camera calibration, however, for this study, only calibrations that resulted in maximal marker localization errors of < 0.7 mm were followed by data acquisition sessions. Spatial resolution of the system is determined by the size of the markers that are used during motion capture, in our case, 2mm. In Cortex, specific markers are identified and labeled by hand, and through this manual process, upper limb 'Templates' that are related to specific sets of markers can be 'trained' to automatically identify unnamed markers in order to eventually enable online marker identification (Fig. 2). Templates are also made more robust by the use of 'linking' between markers: a procedure that sets specific spatial relationships (within a user-defined tolerance) to pairs of markers in the set.

TABLE 1: Upper limb DOFs measured in this study.

DOF	Joint(s)	Description
1	Shoulder	Elevation
2	Shoulder	Elevation angle
3	Shoulder	Rotation
4	Elbow	Flexion/Extension
5	Forearm	Pronation/Supination
6	Wrist	Flexion/Extension
7	Wrist	Ulnar/radial Deviation
8	Digit 1 (Carpometacarpal joint)	Flexion/Extension
9	Digit 1 (Carpometacarpal joint)	Abduction/Adduction
10	Digit 1 (Metacarpophalangeal joint)	Flexion/Extension
11-14	Digits 2-5 (Metacarpophalangeal joints)	Flexion/Extension
15-18	Digits 2-5 (Metacarpophalangeal joints)	Abduction/Adduction
19	Digit 1 (Interphalangeal joint)	Flexion/Extension
20-23	Digits 2-5 (Proximal Interphalangeal joints)	Flexion/Extension
24-27	Digits 2-5 (Distal Interphalangeal joints)	Flexion/Extension

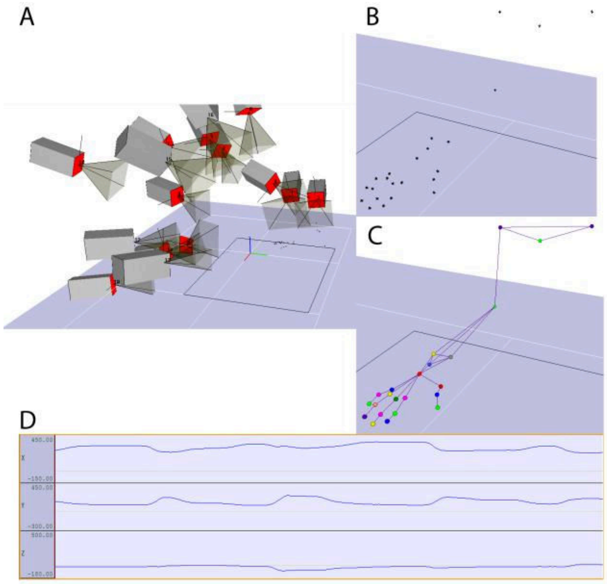

Figure 2. Screen capture showing the detected markers in the context of the full motion capture "world" (cameras shown; A). A set of unlabeled, markers that were detected by the motion capture system (B), are then identified as markers on the upper limb (with associated links between the markers) by a 'trained' template (C). The position of each marker is then tracked in 3D space (D), so that this information can be used to calculate joint angles.

III. BUILDING A SKELETAL MODEL

In order to use marker location in an anatomical context to calculate joint angles, a detailed skeletal model of the *Macaca Mulatta* upper limb is needed. We obtained three T1-weighted MRI scans (slice width 0.7 mm) of the right upper limb of one of the experimental animals, and averaged together to improve MRI scan signal-to-noise. We then built three-dimensional models of the bones required to form the upper limb joints being studied in this experimental paradigm (Table 1; 30 bones) from the MRIs using 3D Slicer (Harvard, MA). Once the bones had been replicated, we imported them into SIMM (Musculographics, Inc), a specialized program that constructs a kinematic model necessary to solve joint angles based upon the captured marker positions imported from Cortex. The kinematic model used by SIMM was custom-designed for macaque anatomy, but based upon the initial work of Holzbaur and colleagues [14]. X-rays were performed on each animal, and bones of the upper limb were measured on these scans, so that a specialized kinematic model could be applied to each animal in order to adjust for individual differences in bone length.

SIMM also interfaces with Cortex in order to build a segmental model based upon marker position in Cortex (Fig. 3B). Creating the segmental model (rather than using an anatomically correct skeletal model) is a useful way of compressing the amount of data that needs to be exported out of Cortex in order to drive the avatar in the virtual environment. However, movement of the segmental model at all joints is still constrained by an anatomically correct kinematic model, ensuring that the segment's movements conform to the anatomical structure of each joint represented by those segments. This allows the macaque avatar to move through a virtual environment in a realistic manner, emulating the actions of actual upper limb joints.

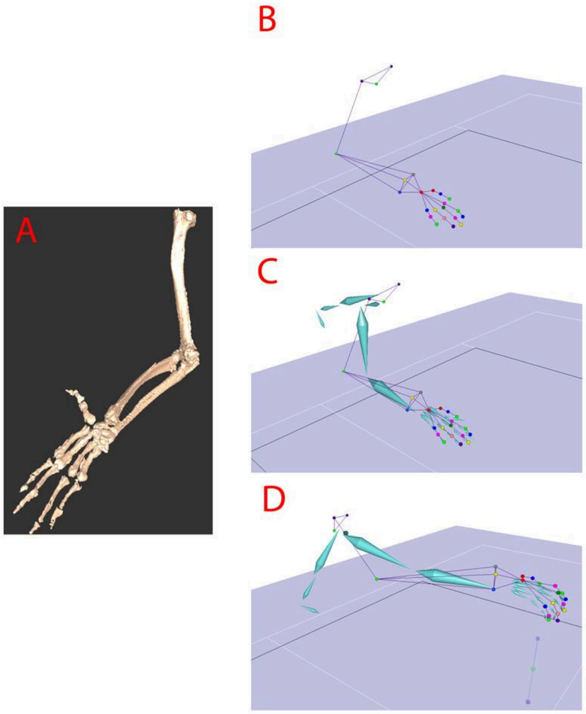

Figure 3. Following construction of a macaque skeletal model based upon MRI scans (A), labeled sets of markers (B) are interfaced with SIMM to generate a segmental model (C). Once the model has been generated, the segments accurately track marker position (D).

IV. BUILDING THE AVATAR

Creating a visually realistic upper limb avatar is an essential step in the process of creating the virtual prosthetic. Graphic artists from Worldviz (Santa Barbara, CA) created a realistic *Macaca Mullata* avatar in Autodesk's 3Ds Max (San Francisco, CA). The segmental model created in Cortex (Fig. 3B) was also exported to 3Ds Max so that it could be bound, and drive movements in the avatar based upon marker position. The use of commercial software tools demands caution due to their tendency to produce realistic movements without regard for anatomical accuracy [6] . However, this particular avatar was custom designed with anatomical accuracy in mind, and increased vertex density at each joint allows for natural movement of the skin over the segmental model that is bound to it (Fig. 4A). Once the avatar is completed, it is exported from 3Ds Max to Vizard (Worldviz, CA). Vizard is a commercially available toolkit that can be used to build and drive customized virtual environments. It was selected for this project due to its ability to interface with Cortex.

V. CLOSED-LOOP CONTROL OF A 27 DOF UPPER LIMB AVATAR

The completed avatar is programmed into a Vizard virtual environment, and via a customized software interface (Worldviz LiveCharacters), coordinates of segmental data information is streamed from Cortex to Vizard in real-time over a local or remote server. This same process can be used to simultaneously animate and track avatars of the objects that the animals are trained to interact with during recording sessions (Fig. 4B, C). The streamed segment information is sufficient to drive the upper limb avatar accurately across 27 DOFs, with a lag time of 30 ms from the moment of motion capture to the re-enactment of movement in the virtual environment.

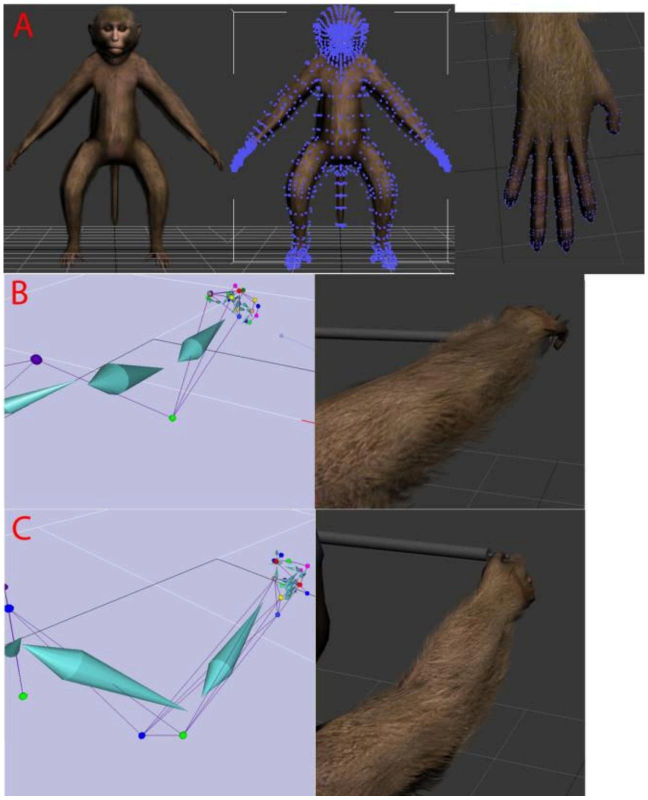

Figure 4. A detailed macaque avatar was developed in 3Ds Max by the graphic artists at WorldViz, the vertex maps (blue dots along the surface of the avatar's surface) show increased vertex density in regions that have higher motor control demands, especially on the hands (far right; A). It is this increased vertex density that allows the avatar to move with realism when driven by kinematic data. Examples of the avatar (right) mirroring power (B) and precision grasping (C) actions performed by the segmental model in Cortex.

VI. CONCLUSION

We have developed a novel method for the closed loop control of an anatomically accurate upper limb virtual prosthetic. Control of a virtual prosthesis across 27 DOFs in real-time is an important step in field of BMI technology. Furthermore, the methodology utilized to develop this prosthetic is not necessarily limited to use in the upper limb and can, in principle, be applied to complex joint models elsewhere in the body.

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