TRAJECTORY CONTROL FOR A MYOELECTRIC PROSTHETIC WRIST

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ABSTRACT

We present a novel method for controlling a myoelectric prosthetic wrist. Five multiple degree-of-freedom (DOF) wrist trajectories are obtained from healthy participants that performed tasks that span the range of Activities of Daily Living (ADL) using dimensionality reduction and unsupervised machine learning techniques. The efficacy of these motions is tested as part of a pilot study where a participant used a simulated wrist device controlled using two-site surface electromyography (sEMG); two trajectories were tested in an immersive virtual reality. Novel wrist control has been demonstrated to be more intuitive to use and appears more natural while limiting the amount of body compensation.

INTRODUCTION

Orienting the hand has been shown to be as important as finger dexterity in aiding us perform Activities of Daily Living (ADL) [1]. Prosthetic devices featuring a wrist, however, have either only 1 or 2 degrees-of-freedom (DOF), largely due to a lack of intuitive control associated with orienting a hand in 3-DOF rotation space while operating each orthogonal DOF independently. Our work focuses on developing an intuitive control strategy for a 3-DOF prosthetic wrist device by taking advantage of joint angle synergies and identifying predefined wrist orientation trajectories that do not require users to independently control each DOF.

Synergies have been identified across different joints in the human body [2], and have been demonstrated to be effective in prosthesis use [3]. Some joints are also predictably coupled [4]. We found inspiration in these findings and identified sets of predefined full arm shoulder-elbow-wrist trajectories using unsupervised machine learning techniques that clustered whole wrist movements into defined sets [5]. The arm movements corresponded to healthy individuals performing a comprehensive set of activities of daily living (ADL). We implement a similar approach to identifying clusters of wrist movements, following with an averaging algorithm to obtain a small, yet representative, set of wrist trajectories.

Virtual Reality (VR) has been used across many domains dealing with the human hand. It can be a valuable tool for training the use of myoelectric prosthesis [6], and can be truly immersive; demonstrated through its capability to treat phantom limb [7]. We make use of advances made in VR technology to demonstrate the capacity of the proposed wrist trajectory control to be a practical approach to operating all 3-DOF of a prosthetic wrist.

METHODS

Wrist Trajectories

We obtained a set of representative wrist trajectories through a series of dimensionality reduction techniques. We first collected 12 healthy subjects (age 24-71) performing ADL using motion capture; 12 Bonita Vicon cameras tracked markers placed around the subjects' forearm and hand. The set of ADL were inspired by work done on upper-limb rehabilitation and prosthesis use evaluation [8], and include the following: drinking from cup or mug placed in various locations, transferring a suitcase or a box, reaching to a can overhead, pouring from a cup, eating with a fork or spoon, reaching to the axilla, and reaching to the back pocket; listed in more detail in our previous work [5].

Joint angles were extracted from marker data and clustered using Hierarchical Clustering with Ward's Distance measure, using dynamic time warping (DTW) to measure the similarity between motions. The number of clusters was identified using the L method. Each cluster was averaged using DTW barycenter averaging (DBA) to distil the large set of motions to a small set of representative wrist trajectories. This study protocol was approved by Yale University Institutional Review Board, HSC# 1610018511.

Control Modes

Participants completed the series of tasks using two types of wrist control: sequential control, and the proposed novel trajectory control. Sequential control interpreted the flexion sensor as driving the wrist along the positive angle direction while the other sensor drove the wrist in the opposite direction at constant speed. A co-contraction cycled the mode from *pronation-supination* to *flexion-extension* to *ulnar-radial deviation*, with pronation, flexion, and ulnar deviation being the positive directions.

The identified wrist trajectories are implemented in our proposed trajectory control. In this setup, the flexion sEMG sensor drove the wrist forward along a selected trajectory, while the extension sensor drove the wrist backwards along the trajectory at a constant speed. A co-contraction results in the cycling between the five trajectories. Each of the trajectory control modes have a defined start and end point. Therefore, even for sequential control conditions, the wrist began in the same orientation as the trajectory control.

Control Input

We used HTC Vive for both the head tracking and for the head mounted display (HMD). The participant's forearm was tracked and displayed within the virtual environment (VE), implemented in Unity, to provide a point of reference for the hand orientation. This was done using Vicon to track markers placed around the forearm and streamed to Unity. To control the virtual hand, the participant's forearm was also outfitted with two surface electromyography (sEMG) sensors, placed on the flexor and extensor muscle groups (see Figure 1), connected to an Arduino Uno. Sensor readings were translated to either *on* or *off* according to a calibrated threshold value.

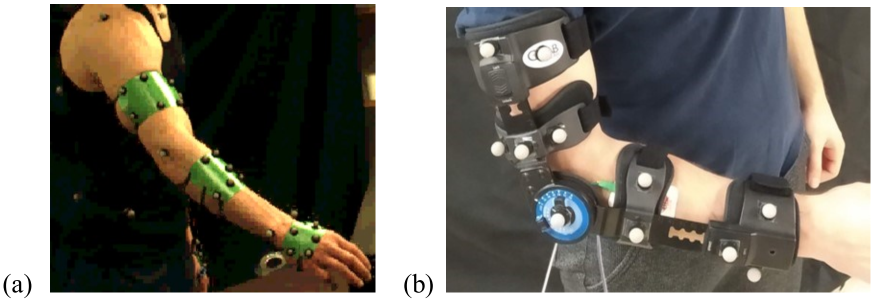
(a) (b)

Figure 1: (a) Marker set used to collect healthy arms motions that were then used to generate the wrist trajectories. (b) The elbow brace was used to maintain the reflective marker arrangement, such that the virtual forearm and humerus segments are automatically detected and displayed within VR. The brace's range of motion was set to maximum and was not used to limit the elbow motion itself. sEMG sensors placed over the skin around the forearm can be seen underneath the elbow brace.

Pilot Study Procedure

In this pilot study, one healthy right-handed participant (male, age 28) performed two tasks related to ADL in VR by attempting to align the end effector with the desired goal. The subject did not have any visual or motion impairment and was comfortable using VR. Tasks included in this pilot study are described in more detail in Table A. Because each trajectory control mode corresponds to a specific task, these were included in the table for reference. Only two tasks were tested in this pilot, therefore only trajectories (4) and (3) (see Figure 2 for detail) were used, for reaching to the cup and pouring with the cup, respectively. Prior to each task, the participant was given ample time to practice and develop a strategy that they're comfortable with using during the task recording; the purpose was simulate the performance likely achieved by an experienced user. For tasks involving object transfer, objects were automatically placed within the hand.

Table 1: Pilot tasks

Task	Task description	Corresponding wrist trajectory
Reach to cup	Standing, starting with the hand by the side, reach to the cup on the table	(4) supination/extension
Pour from cup	Sitting, transfer the cup from the table to the pouring location and orientation	(3) supination/flexion

Evaluation

The participant's performance can be assessed in various ways. Because the goal is to improve prosthesis use in the real world, we wanted to focus on the time it takes to complete a task and the motion cosmesis. The participant also provided feedback and helped guide our interpretation of his performance. While cognitive effort to control the prosthesis was not directly measured, it may be inferred from the time measurements.

RESULTS

Wrist trajectories were obtained through averaging each of the motion clusters. Although each consists of a 3-DOF wrist rotation, they can be better described according to the dominant DOFs as follows: (1) *supination/ulnar deviation* (2) *flexion/ulnar deviation* (3) *supination/flexion* (4) *supination/extension* (5) *extension-ulnar deviation*, as seen in Figure 2. Two of these wrist trajectories, (3) and (4), were used in the pilot study.

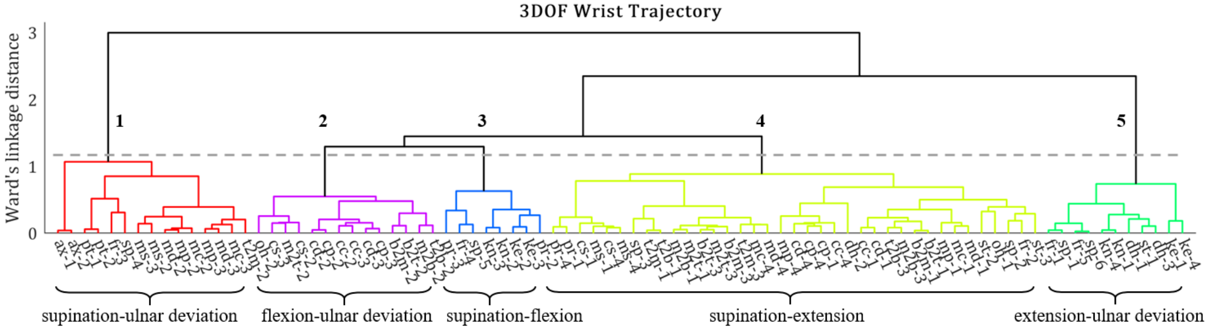

Figure 2: Hierarchical clustering results. A horizontal cut segmented the dendrogram into five clusters of motion. A descriptive label is included for each cluster.

Recorded wrist joint motion trajectories for each of the trials are displayed in Figure 3. Motions were segmented according to when the participant's hand began to move and when the target end effector position and orientation, was reached.

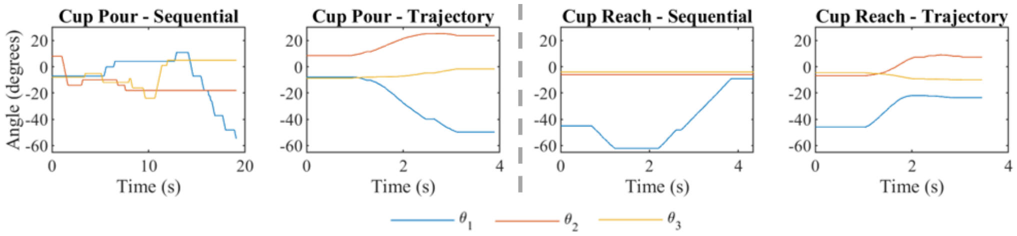

Figure 3: The 3-DOF wrist joint angle trajectories are displayed for each trial. θ_1, θ_2, and θ_3 correspond to pronation, flexion, and ulnar deviation respectively. The left two plots correspond to the cup pouring task under the two different control strategies, sequential and trajectory control, while the right two images correspond to the cup reaching task. Wrist rotation did not necessarily begin when the hand started to move.

The participant was able to complete both tasks faster using trajectory control. Sequential control for the cup pouring task took significantly longer than when using trajectory control, while the times were much closer for the cup reaching task. This is likely because the task required switching between the different joint angles, which can be challenging, or even confusing, for the user. The cup reaching task did not require switching between the different DOF, and supination alone was sufficient.

Wrist motions appeared more naturally under trajectory control. This is largely due to the lack of access to all 3-DOF of the wrist during sequential control, as is evident in Figure 3. Without haptic feedback, the user appeared to be looking down at their simulated device. This was exacerbated when multiple mode switching was required, such as for the cup pouring task with sequential control. Trajectory control for both tasks did not require mode switching, since a single mode, corresponding to the respective task, was sufficient.

DISCUSSION

In this study we were able to gain significant insight into our proposed wrist trajectory control that encourages further investigation. In this preliminary study, trajectory control has been demonstrated to be a superior alternative to sequential control, despite limiting users to specific wrist orientations. Findings further demonstrate the capacity of joint synergies to simplify control. Trajectories appeared to generalize well to the tasks, without requiring the user to compensate with their residual limb or torso.

During the experiment, when using sequential control, the participant generally relied on fewer DOF than were available. This was likely the easiest way to control the wrist without having to repetitively switch between DOF. This showcases the benefits of trajectory control whereby all 3-DOF of the wrist are at use while maintain a simple and intuitive control strategy.

We must also acknowledge that there were learning differences between the two control strategies. While sequential control would task users to learn the correct order of rotations, trajectory control requires a memorization of which tasks belong to which motion control. In the future, training time and cognitive load will be addressed.

Using state of the art motion tracking, HMD, and control input, we believe this is the closest a simulation can get to testing prosthesis without using the actual prosthetic device. Innovations in this field have the potential to streamline prosthesis design iterations, prosthesis training, and rehabilitation [9], [10]. However, there are certain drawbacks that need to be addressed in the future in order to fully bridge the gap between simulation and reality. These include adding haptic feedback, inertia, wider field of view and resolution in the HMD, and improving the realism of the virtual environment design.

In future iterations of this experiment we will recruit additional subjects and expand on the tasks. We will also include alternative state of the art control strategies, such as enabling participants to simultaneously control DOF. Positive and negative controls will be included as well, corresponding to tracking the users' hand while unrestricted and fully restricted, respectively.

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