Visual Discrimination of Biomimetic Arm Speeds

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***Abstract*— Fine control of robotic prosthetic limbs requires repeatable command signals and comprehensible feedback. However, robotic prostheses currently lack this sensory feedback. Artificial sensory feedback can help users control their prosthesis, but sometimes users choose to rely on vision over this feedback. This suggests that vision can provide the same information as this artificial feedback, but is more trusted. To provide feedback that is not redundant with vision, we should provide information vision cannot provide well. Previous research suggests vision is less precise at estimating speeds than positions. Our work expands this previous knowledge by specifically investigating visual speed perception of biomimetic arm movements. We show that visual uncertainty is greatest when estimating joint speeds, especially when the reference frame speed varies over time. Thus, artificial feedback of joint speed may be more likely to integrate with vision and improve prosthesis control.**

I. Introduction

SENSORY feedback for robotic prosthetic limbs is a research priority for many prosthesis users [1]. Aside from modern research devices, prostheses are not capable of directly replacing the missing proprioceptive information of the state of the limb. Thus, prosthesis users visually monitor their prosthesis while in use to restore some of this missing proprioception [2]. Many attempts to provide artificial feedback have been successful while the prosthesis is obscured, but this benefit sometimes diminishes when the prosthesis is in view. This suggests the artificial feedback is providing similar information to vision, but with greater uncertainty, and users therefore choose to rely on vision over artificial feedback [3].

To avoid providing redundant information, artificial feedback should strive to provide information not provided, or provided poorly, by vision. Previous research suggests vision estimates position with high precision [4], but estimates speed with much lower precision [5]. Speed can be defined in several biologically-appropriate reference frames. For example, movement of the elbow can be defined relative to the environment (absolute speed), or the movement of the shoulder (joint speed). However, visual uncertainty associated with these biomimetic arm movements has not been quantified.

In this study, we investigate visual joint speed perception in the context of providing artificial proprioceptive feedback for prosthetic limbs. Subjects participated in a two-alternative forced choice task observing a virtual two-arm link to determine just noticeable difference (JND) thresholds for different types of arm movements. Additionally, we tested how joint speed JND changes as a result from inconsistent reference frame speeds.

II. Methods

A. Setup

Subjects sat in front of a computer monitor and shown a pair of black two-link systems, similar to a top-down view of a shoulder and elbow, with link lengths of 5cm and endcap diameters of 2.1mm (Fig. 1). These were presented for 2 second each, separated by a 1 second pause.

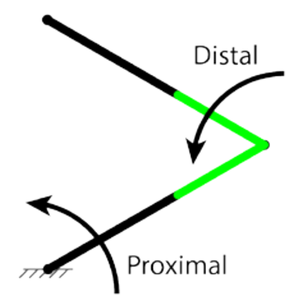

Fig. 1. A two-link system served as the visual stimulus for two-alternative forced choice tasks. In Condition 1, subjects identified which proximal link they perceived was moving faster, and in Condition 2, subjects identified which distal link they perceived was moving faster, relative to the proximal link. In Condition 3, subjects observed the speed of the distal link, but the proximal link moved at different speeds between the two stimuli.

B. Protocol

Subjects completed two-alternative forced choice experiments designed to quantify visual speed discrimination. During a trial, the two-link system was displayed to subjects twice. Three conditions were tested, corresponding to visual discrimination of rotational speeds prosthesis users may experience during daily prosthesis use. For each condition, three nominal speeds were tested: 30 °/s, 60 °/s, and 120 °/s. The starting position of the proximal and distal links were randomized for each stimulus, and the distal link was resampled as needed to prevent it from crossing the proximal link.

The first condition tested visual discrimination of absolute rotational speeds, relative to a static global reference frame (i.e. the screen). During each trial, the proximal link in one stimulus would move at the prescribed nominal speed, and

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in the other stimulus would move at a speed as defined by an adaptive staircase:

$$x(n+1) = x(n) - \frac{C}{n_{shift}+1}[z(n) - \phi]$$

where x was the difference in movement speeds between stimuli, C was the starting speed difference (50%), *nshift* was the number of decision reversals, ϕ was the target JND probability (84%), and z was a Boolean indicator for the subject's decision (z = 1 when correct and z = 0 when incorrect) [6]. This adaptive staircase converged on the 84% JND after 25 decision reversals. The distal link in both stimuli started at 60 °/s and was randomly accelerated and decelerated. Thus, the speed profile was identical between stimuli.

The second condition tested visual discrimination of joint speeds relative to a reference frame (i.e. the proximal link) rotating at consistent speeds between stimuli. During each trial, the distal link in one stimulus would move at the nominal speed (relative to the proximal link), and the other stimulus would move at a speed defined by the adaptive staircase above. The proximal link in both stimuli started at 60 °/s and was randomly accelerated and decelerated. Thus, the speed profile was identical between stimuli.

The third condition tested visual discrimination of joint speeds relative to a reference frame rotating at inconsistent speeds between stimuli. During each trial, the distal link in one stimulus would move at the nominal speed (relative to the proximal link), and the other stimulus would move at a speed defined by the adaptive staircase above. The proximal link in one trial moved at a constant speed of 60 °/s in one trial, and a constant speed of 120 °/s in the other trial.

C. Data Analysis

The 84% JND obtained from each experiment was converted into uncertainty (i.e. standard deviation) of the underlying estimator by dividing by √2 [7]. This uncertainty was then normalized and used as the outcome metric for the results presented in Fig. 2.

III. Results

Visual uncertainty was lowest when assessing the speed of the proximal link, ranging between 20% and 30% (Fig. 2). Visual uncertainty increased when subjects assessed the speed of the distal link relative to the proximal link, with uncertainty ranging between 30% and 50%. When the speed of the proximal link was inconsistent between stimuli, distal link uncertainty tended to increase further, but this increase was not significant. Across all conditions, uncertainty was highest when assessing slow nominal speeds. This trend is particularly prevalent during distal link assessments; at the slowest nominal speed, the distal link being assessed is moving half as fast as the proximal link.

IV. Discussion

Given two sources of information, humans make a single estimate by integrating the two sources, weighted by their

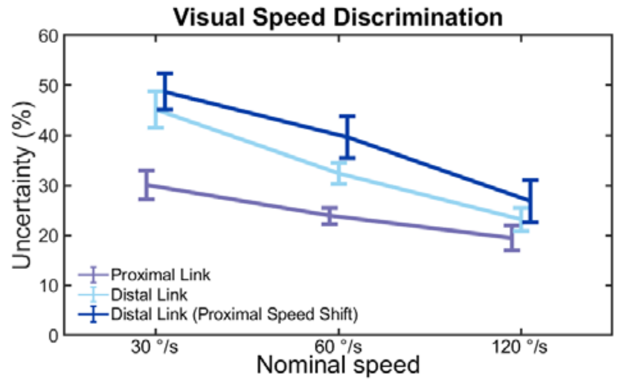

Fig. 2. Uncertainty for visual speed discrimination of the proximal link was between 20% and 30%, while uncertainty for visual speed discrimination of the distal link was between 30% and 50%.

uncertainty [3]. Thus, they rely more heavily on the source with lowest uncertainty. Therefore, to suitably replace a missing source of biological feedback with artificial sensory feedback, this feedback should have similar or lower uncertainty than remaining senses, notably vision.

In the context of providing feedback for prosthetic limbs, our results suggest providing proprioceptive feedback in terms of joint speeds defined relative to more proximal body segments, as opposed to absolute speeds defined relative to the torso or the environment. Because of the greater uncertainty associated with visually estimating the speed of the distal link (i.e. joint speed), artificial feedback providing this information is likely to provide the greatest improvement to restoring limb proprioception. This improvement may increase further as the speed of the reference frame increases (e.g. proprioception of elbow movement as the shoulder is in motion). We aim to develop a feedback system which improves joint speed perception and integrates meaningfully with vision, which may lead to and improved sense of proprioception and embodiment of prosthetic limbs and improved control during daily tasks.

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