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Quantifying the Value of Visual and Haptic Position Feedback During Force-Based Motion Control

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Quantifying the Value of Visual and Haptic Position Feedback During Force-Based Motion Control

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Abstract

Controlling the motion of a prosthetic upper limb without visual feedback is extremely difficult because the wearer does not know the prosthesis' configuration. This paper describes an experiment designed to determine the relative importance of visual and haptic position feedback during targeted force-based motion by non-amputee human subjects as an analogy to prosthetic use. Subjects control the angle of a virtual proxy through an admittance relationship by generating torque at the MCP joint of the right index finger. During successive repetitions of a target acquisition task, the proxy's state is selectively conveyed to the user through graphical display, finger motion, and tactile stimulation. Performance metrics for each feedback condition will provide insights on the role of haptic position feedback and may help guide the development of future upper-limb prostheses.

1. Motivation

Upper-limb prostheses seek to seamlessly replace the user's missing appendage, but current devices cannot yet match the functionality of an intact human arm and hand. An extensive 1996 survey of American individuals with upper-limb loss or absence provided valuable insights on the priorities of arm-prosthesis users: the development of a system that "required less visual attention to perform functions" was highly requested [2]. This goal of unsighted operation was out of reach at the time, as available prostheses provided no substitute for proprioception, the human ability to haptically sense the relative position and orientation of one's body parts. Extensive research has documented the necessity of proprioception for natural human motor control [7], but little work to date has investigated its potential contribution in prosthetics [1].

This research seeks to ascertain the relative value of visual and haptic position feedback for controlling the motion of a non-self entity like a prosthesis. Many multi-articulating, powered, highly-sensorized upper-limb prostheses are currently being developed: to stand in for the human arm, such prostheses are typically driven by electrical signals recorded from the user's residual arm muscles [6] or motor neurons [4], which both correspond well to muscle force. The electrical and mechanical design of the arm and the properties of its environment determine the means by which this sensed user force generates prosthetic hand motion. Operating a modern prosthesis is thus similar to controlling the movement of a virtual or remote proxy through an admittance-type (non-backdrivable) haptic interface, which also measures user force and optionally provides position feedback [3]. This paper describes a human-subject experiment on the usefulness of haptic position feedback during general force-based motion control; results that substantiate its importance will help stimulate and guide efforts to provide high-fidelity prosthetic proprioception.

2. Experiment design

Non-amputee human subjects will be asked to control the motion of a force-based finger proxy in a simple virtual environment. The assigned task is to repeatedly move the proxy to a designated target zone as quickly and accurately as possible. As depicted in Fig. 1, the proxy has one rotational degree of freedom, $0^\circ \leq \theta_p \leq 90^\circ$, matched

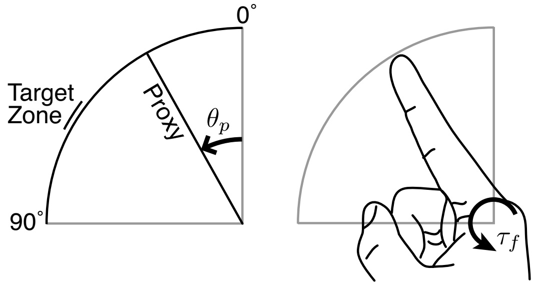


Figure 1. Proxy position and finger torque.

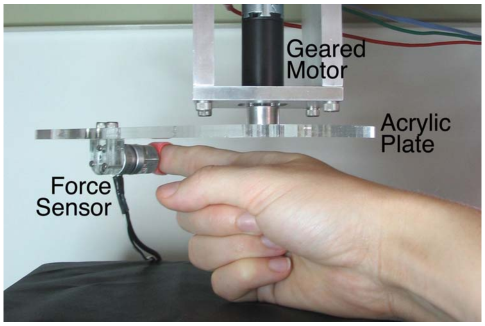
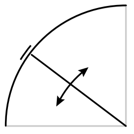
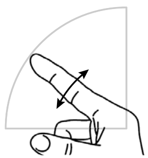
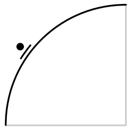
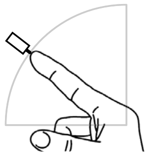


Figure 2. Experimental apparatus.

Table 1. Proxy Position Feedback Modalities.

	Visual	Haptic
Analog Motion	 *Line Segment*	 *Finger*
Binary Success	 *Dot*	 *Contact*

to the rotation of the right index finger about the metacarpophalangeal (MCP) joint. The user controls the motion of the virtual proxy by generating torque, τ_f, at the MCP joint. The proxy's velocity, $\dot{\theta}_p$, is programmed to be directly proportional to the applied finger torque, mimicking a rotational damper. This simple dynamic relationship was chosen because it allows the user to stop the proxy easily at any position by applying zero torque.

The subject controls the virtual proxy through the custom haptic interface pictured in Fig. 2. The apparatus is composed of an aluminum base structure, a geared motor with attached encoder, a clear acrylic plate affixed to the motor shaft, and an ATI Nano17 force sensor. During use, the user rests his or her right hand on a support below the apparatus, such that the index-finger MCP joint aligns with the motor shaft. The fingertip is attached to the surface of the force sensor by a Velcro loop. The radial position of the force sensor is adjusted for each user to the appropriate finger length, and this distance is used to compute finger torque from measured fingertip force.

Subjects will perform many trials of the target acquisition task, pushing and pulling with the fingertip to move the proxy to a series of target zones shown on the computer screen. The trials are broken up into randomized sets, each of which provides the user with a unique combination of the four position-feedback modalities listed in Table 1. The two visual feedback methods are displayed via the computer monitor: a moving line segment is used to continuously convey the proxy's position, and a dot is used to signal that the proxy is inside the target zone. The two haptic feedback methods are provided via the apparatus: its nonbackdrivable motor is used to move the finger continuously to the proxy's position, and its solenoid (not visible in Fig. 2) is used to contact the fingertip to signal that the proxy is inside the target zone. The apparatus itself is hidden from the subject's view, and its sounds are masked by white noise.

Proxy position will be recorded for the duration of each trial, along with the active set of experimental conditions. This data will be analyzed in the framework of Fitts' Law, a well-studied tool for evaluating targeted human motion [5]. After performing a full set of tasks, subjects will also assess the qualitative ease of use of each condition by completing a questionnaire. Our primary hypothesis is that analog haptic feedback of proxy position, which is perceived via finger proprioception, will improve task speed and appeal to subjects, especially in the absence of continuous visual position feedback. Findings about the interaction between visual and haptic modalities, as well as the effects of analog versus binary feedback, will further our understanding of force-based motion control and inform future work in both haptics and prosthetics.

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