Real-time haptic-teleoperated robotic system for motor control analysis

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Abstract

A versatile teleoperated robotic system was created as an assessment device for testing upper-extremity motor control adaptation using different control strategies. While many systems display output virtually on a computer monitor, this system was designed to output in three-dimensional physical space. The system accepts haptic force and torque input, and outputs robot end-effector displacements and rotations in three spatial dimensions. Benefits of this system include flexibility to conduct a variety of dissimilar tasks and reality of user feedback in physical space. Two separate experiments validated the teleoperated robotic system. The first experiment tested unimanual human motor control and the second tested bimanual motor control. This teleoperated robotic system can be used as an assessment device to study neuromuscular adaptability via a variety of control strategies providing a new and functional approach to human motor control analysis.

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1. Introduction

Both virtual and physical environments (Fig. 1) can be used to test subjects on motor control strategies. A virtual environment portrays the user’s output through a computer simulation, while a physical environment displays physical output in three-dimensional space. Virtual environments generally lack the ability to display depth perception and multiple degrees of freedom (only complex simulations have this capability). In a manipulandum-based system, input is collected from subjects using the manipulandum and output is virtual, shown on a computer monitor. Manipulandum-based systems are being used to test human arm adaptation to external environments, such as viscous force fields (Scheidt et al., 2000), position-dependent force fields (Franklin et al., 2003), velocity-dependent force fields (Donchin et al., 2003) and unpredictable force fields (Scheidt et al., 2001). This system provides a physical output environment that gives the user physical feedback in three spatial dimensions. Benefits of such a system include flexibility to conduct many different tasks in multiple dimensions and reality of user feedback in three-dimensional physical space.

2. Teleoperated system

Haptic signals are measured as input and robot end-effector displacement is displayed as output in the teleoperated robotic system (Fig. 2). Input to the teleoperated system is haptic forces and/or torques measured by the rigid joystick fixture. Based on a predetermined control strategy, the inter-

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Fig. 1. Examples of teleoperation via a virtual environment and a physical environment. In both systems, the rigid joystick is used to measure haptic forces and torques as inputs. In a virtual environment, virtual movement output is displayed on a computer monitor, while physical environment movement is physically represented via a robot end-effector.

facing computer converts input signals to end-effector linear and rotational displacements and sends the results as a displacement matrix to the robot controller. The robot controller then initiates end-effector motion based on the displacement matrix.

Haptic forces and torques are measured by the six degree-of-freedom load cell through the rigidly attached joystick. Plastic suction clamps attach the entire fixture to a smooth surface. A wire connects the load cell to the interfacing computer for force and torque data transmission. Input signals are sampled, processed and relayed to the robot by the interfacing computer through a data acquisition card. Using a preprogrammed control strategy, a LabVIEW software program maps the input signals into a displacement matrix composed of linear and angular displacements. Different control strategies can be evaluated by changing the software control strategy parameters. The displacement matrix is transmitted as an array to the robot controller.

The robot controller provides serial input/output (I/O) and data processing and initiates robot movement. Input displacement data relative to the end-effector’s current spatial position is received through the serial I/O module. A V+ software program run by the controller’s primary processor uses the displacement data to actuate robot motion. The robot initiates movement to a new position dictated by the relative displacement data. Once the robot reaches the desired position, it smoothly transitions to the next displacement position. To the user, robot motion appears to be continuous and in real time.

An AdeptOne robot provides the physical output environment in the real-time robotic system (Fig. 5). Four joints of the robot enable end-effector movement in three spatial dimensions. Joints 1 and 2 provide approximately 300° of rotation about each respective joint vertical axis, while joint 3 provides 554° of rotation about the vertical axis and 295 mm of translational displacement along its vertical axis. Joint 4 provides 180° of rotation about its horizontal axis. The pneumatic gripper has an open and a close position. All rotational joints have vertical rotational joint speeds of at least 540° s⁻¹ (Fig. 3).

3. System validation

3.1. Unimanual experiment

A unimanual human motor control adaptation experiment was conducted using two distinct haptic non-intuitive I/O control strategies. The purpose of the experiment was to determine whether subjects could adapt by improving performance using their respective control strategies. Subjects were positioned approximately 1.5 m from the testing board and used haptic forces and torques as input to initiate end-effector motion (Fig. 4). Four subjects used a haptic direct control strategy. Using this strategy, torques about the joystick z-axis produced x-axis displacements of the end-effector and forces along the z-axis of the joystick produced y-axis displacement of the end-effector. A separate group of five subjects used
Fig. 2. Teleoperated system. The interfacing computer measures test subject haptic force and torque signals, which are used as input to the teleoperated system. These input signals are then converted to an output displacement matrix by the interfacing computer, based on a predetermined control strategy. The robot controller receives the output displacement matrix and uses it to initiate robotic end-effector movement.

an indirect control strategy, in which input torques about the joystick z-axis produced joint 2 (J2) angular displacements and input z-axis forces produced joint 1 (J1) displacements (Fig. 4).

All subjects were given the task of following a predetermined, two-dimensional path at varying predetermined velocities with the end-effector of the robot arm. Each trial lasted approximately 30 s. The task was identical for each group of subjects, but the control strategy was different. Subjects did not know their control strategy but had to determine how to purposefully move the end-effector to follow the path. Their level of performance was measured by how closely they were able to follow the path spatially and temporally.

Subjects’ test data was grouped into blocks of eight trials and fit with exponential least squares regression curves of the form: $y = ae^{bx} + c$ (Fig. 5). Evaluation was based on mean error, which was the average distance in centimetres between the experimental and desired path during the entire trial. The standard deviation of the mean error during the trial was the standard deviation error. Results show that subjects using both direct and indirect control strategies continually improved since their mean and standard deviation error scores continually decreased, though subjects using the direct control strategy improved more quickly than those using the indirect control system marked by a steeper slope in the exponential curve. None of the subjects reported any difficulty with the 1.5 m distance between the subject and the testing board. Neither did any of the subjects’ scores normally decrease as the robot arm moved farther from the subject. It was thus assumed that depth perception did not adversely affect subject performance. This experiment demonstrated that the presented teleoperated robotic system is useful for testing two distinct motor control strategies.

3.2. Bimanual experiment

A bimanual experiment was performed to further verify the real-time robotic system as a valid system for testing motor control (Shull and Gonzalez, 2005). A group of 10 subjects used an indirect haptic control strategy to control the end-effector of the robot arm. Subjects had to trace 15 cm circles at 3.2 s intervals in the clockwise direction (Fig. 6). They completed two stages of testing. In the first stage, subjects traced a circle with the end-effector of a robot arm by using
Fig. 3. AdeptOne-MV Robot. Joints 1–3 provide rotational displacement about the vertical axis, while joint 4 provides rotational displacement about the horizontal axis. Joint 3 provides translational displacement along the vertical axis.

their dominant arm to apply forces and torques to the rigid joystick. During the second stage of testing, subjects continued to control the robot end-effector with their dominant arm, but they also had to simultaneously use their non-dominant arm to trace another circle.

Controlling the robot arm end-effector was a non-intuitive task. Applying positive z forces to the rigid joystick caused the end-effector to move in the positive x direction, and applying negative z forces to the joystick cause the end-effector to move in the negative x direction. Positive torques applied to the rigid joystick about the load cell’s x-axis caused end-effector positive y displacement, and negative torques about the load cell’s x-axis produced negative y displacements. Subjects were not told the control strategy; they had to determine how to trace the circles through practice.

Trials were grouped into trial blocks of five trials each. The level of performance was measured by how accurately subjects were able to trace the circles spatially and temporally (Fig. 7). Spatial error for each trial was calculated by averaging the shortest distance in millimetres between the circle and the subject’s position during the entire trial. Temporal error was calculated as the average of the angular displacement (absolute value in degrees) between the experimental and desired angular position throughout the trial. Subjects demonstrated learning patterns marked by a decrease in both spatial and temporal error with practice. This bimanual experiment showed that the teleoperated robotic system is useful for testing and evaluating bimanual control strategies for human motor control.

4. Discussion

Robotic end-effector output occurs in three-dimensional physical space, though output can be constrained to fewer dimensions for specific applications. In the unimanual experiment, end-effector output was confined to a two-dimensional plane. However, the plane was horizontal and thus the user had to account for depth perception. Virtual environments can simulate three-dimensional output movement, but programming to make the output realistic to the user can be complex. Changing the simulation for different applications

Fig. 4. Unimanual experimental set up. (A) Test subject, (B) rigid load cell joystick fixture, (C) AdeptOne robot arm with laser pointer on end-effector, (D) desired path on testing board (approximately 200 cm) and (E) robot joint identification and end-effector orientation. Subjects moved the robot arm via forces and torques measured by the rigid load cell joystick fixture. The subject’s path was observed by the laser pointer projection on the board.
Fig. 5. Unimanual experimental mean error and standard deviation of subjects using direct and indirect haptic control strategies. Trials were grouped into blocks of eight trials each and fit to exponential least squares regression curves of the form $y = ae^{bx} + c$. Subjects using both the direct and indirect control strategies demonstrated learning patterns by decreasing mean and standard deviation error scores with practice. Subjects using the direct control strategy learned at a faster rate than subjects using the indirect control strategy.

Fig. 6. Bimanual experimental set up. Subjects were instructed to trace 15 cm circles at 3.2 s intervals in two distinct stages. In the first stage, they used their dominant arm to control the robot arm end-effector by applying forces and torques to a rigid joystick. In the second stage, they used their dominant arm to control the end-effector while simultaneously using their non-dominant arm to trace another circle.

Fig. 7. Bimanual experimental spatial and temporal error of all subjects. Trials were grouped into blocks of five trials each. Subjects demonstrated learning patterns by decreasing spatial and temporal error scores with practice.
may therefore require extensive programming. Our system creates dissimilar experiments of varying complexities, providing the user with realistic feedback and requiring little or no programming changes.

Results from the unimanual and bimanual experiments show that the real-time robotic system can be used as a powerful tool for motor control evaluation. Distinct control strategies can be predetermined and then quantitatively compared and evaluated by analyzing data from subjects using the robotic system. In the unimanual experiment, two specific control strategies were chosen to test subjects' ability to learn to purposefully control a system in which input forces were either directly linked to output motion or indirectly linked to output motion but directly linked to joint rotation. In a similar way, the real-time robotic system could be used to compare and evaluate a variety of other control strategies differing in complexity, difficulty or fundamental operation.

Bimanual experimental results showed that subjects could simultaneously control the robotic system and their non-dominant arm to purposefully complete a task. This experiment was not used to compare two or more distinct control strategies but to critically evaluate a specific element of motor control. Future experiments could be set up with the real-time robotic system to study other aspects of human motor control.

Many teleoperated systems provide force feedback, which gives the operator more complete information. Force feedback causes a system to be sensitive to time delays and prone to instability (Tanner and Niemeyer, 2004), problems that recent research has focused on solving (Kuchenbecker and Niemeyer, 2004). The presented teleoperated robotic system was not designed to provide the operator with force feedback. However, in the future, this capability may be added, and at that time potential instability problems must be resolved.

Applications for the teleoperated robotic system are generally for motor control testing purposes (Ness and Gonzalez, 2004; Slager and Gonzalez, 2001). Like the unimanual and bimanual validation experiments, other similar experiments could be established to test motor control strategies. Both the unimanual and bimanual experiments used the teleoperated robotic system for only two degrees of freedom in the horizontal plane. Future experiments could use three-dimensional output with the added possibility of rotational output.

Teleoperation allows system output to be controlled by system input from varying distances. The length of the wires connecting the system is the only limitation on the range of operation. In the validation experiments, the distance from input to output was relatively short (2 m or less). In the future, the robotic system could conceivably be used over greater distances such that the user could not see the physical environment output. A simulated virtual environment would be set up as feedback for the user, but robotic system output would continue to occur in a physical environment. This application would be useful for teleoperated surgical training purposes.

5. Conclusion

A real time teleoperated robotic system was successfully created to test I/O control strategies. Input through haptic force and torque signals and output in three spatial dimensions make it an effective testing device. Validation of this system has shown that it can be used to test unimanual and bimanual human motor control. This real time, teleoperated robotic system is important as an assessment device for evaluating control strategies in human motor control.

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References


