Driver's SEAT: Simulation Environment for Arm Therapy

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Abstract

Hemiplegia, affecting approximately 75% of all stroke survivors, is a common neurological impairment. Hemiplegic upper and lower limbs exhibit sensory and motor deficits on the side of the body contralateral to the location of a cerebral vascular accident. Recovery of coordinated movement of both upper limbs is important for bimanual function and promotes personal independence and quality of life. This paper will describe the philosophy and design of Driver's SEAT, a one degree of freedom robotic device that aims to promote coordinated bimanual movement.

Introduction

The Driver's Simulation Environment for Arm Therapy (SEAT) is a prototype rehabilitation device developed at the VA Palo Alto Health Care System (VAPAHCS) Rehabilitation Research &Development Center (RRDC) to test the efficacy of patient-initiated bimanual exercise to encourage active participation of the hemiplegic limb. The robotic device is a car steering simulator, equipped with a specially designed steering wheel to measure the forces applied by each of the driver's limbs, and with an electric motor to provide programmed assistance and resistance torques to the wheel.

Background

A variety of upper limb rehabilitation techniques have been used to help improve motor control and physical performance outcomes in subjects with hemiplegia. Despite the varied efforts, studies [e.g., 1,2,3] suggest that upper limb rehabilitation therapy has a less than 50% success rate. However, in some small scale studies, researchers have demonstrated that recovery of arm function may be improved even in chronic hemiplegia. After synthesizing the results of several of these intervention techniques, Duncan [4] noted that forced-use paradigms [e.g., 5,6,7] and enhanced therapy [e.g., 8,9] provided the most promising evidence that motor recovery can be facilitated.

These effective interventions were described as having the following in common: active participation of the patient in tasks, increased practice times outside of therapy sessions, increased involvement of the paretic limb in exercises, and more repetitive training. Besides these elements, other variables, such as early intervention, external motivation, and bimanual exercise, have been proposed as important for successful rehabilitation outcomes. Driver’s SEAT is designed to incorporate many of these key components into rehabilitation therapy.

Driving is a motivational functional task. In his literature review, Katz, *et al*.[10] suggested that cessation of driving in stroke patients is associated with social isolation and depression. Therefore, if the ability to drive can be restored, the resulting independence can reduce a person’s sense of immobility as well as improve their prospects for rehabilitation. In view of this, the motivation to use Driver’s SEAT to improve upper limb performance should be a strong one, since subjects are given the opportunity to practice coordinated steering, a skill integral to driving.

Sustaining motivation throughout a rehabilitation program using Driver’s SEAT is facilitated by transferring some of the responsibility for task success from the therapist to the subject. One suggested method is to engage subjects in patient-controlled exercises. The benefits of patient-controlled exercise are under investigation in another study at the RRDC called “Mechanically Assisted Upper Limb Movement for Assessment and Therapy” study (MIME) [11]. In this study, a six-degree of freedom robot is used to implement bimanual exercises (structured tracking tasks) that allow the non-paretic limb to guide the therapy of the paretic arm. As a result, the person initiates and controls the therapy in a natural way. The level of each subject's recovery determines the type of force intervention given.

Driver's SEAT is designed to use a modified forced-use paradigm to enable subjects to engage their paretic limb. The robotic device will engage muscle groups of the shoulder and elbow in a bimanual exercise that uses a simple (one-degree of freedom) task. Three steering modes are designed into Driver's SEAT to allow the paretic and non-paretic limbs of subjects to interact in three different ways. In each mode, subjects' ability to successfully complete the steering tasks is coupled to their ability to modify the forces they generate on the steering wheel with each limb.

Hardware/Software Design

The hardware has been designed to interface with a low cost PC-based driving simulator designed and built by Systems Technology Inc. (STI) [12]. The value added to the Driver's SEAT system by the STI's simulator is its ability to give realistic graphical road scenes and quantify cognitive and sensory/motor skill recovery using both position and force related performance measures.

The current Driver's SEAT system (Figure 1) consists of a motor, an adjustable-tilt (0°-90°), split steering wheel, a height-adjustable frame, wheel position sensor (optical encoder), wheelrim force sensors, STI's simulation hardware and the experimenter's computer hardware.

In real time, the STI computer generates the graphical scenes and collects various variables associated with the steering dynamics, i.e., lateral acceleration, steering angle and yaw rate. The angular position of the steering wheel controls the lateral position of the car image on the generated roadway scene. A typical road scene is designed using STI’s scenario definition language. The scene is made to appear 3D and the roadway moves towards the driver as a function of speed. Several road scenes, designed to last no longer than 3 minutes, give users the "feel" of rural, suburban, and urban driving.

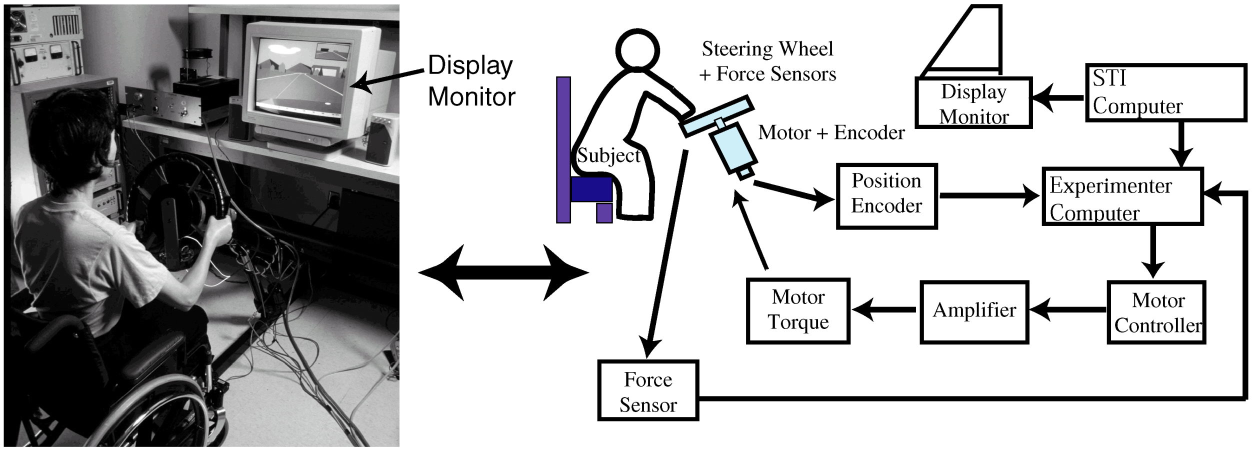

Figure 1: Driver’s SEAT System

Throughout this paper, steering tasks are defined as the roadway scene and the set of instructions given to the drivers to guide them in navigating the scene. Thus, a steering task is designed such that if users follow the experimenter’s instructions and 1) navigate the roadway scene in such a way as to keep their car icon tracking a road edge line and 2) coordinate their limbs as instructed, they would experience success. Steering tasks are implemented without user-controlled accelerating and braking in order to allow users to concentrate solely on steering. The speed of the scene is set a priori and remains constant throughout the task.

The experimenter’s computer is the nucleus of the Driver’s SEAT system. Through a series of menus, the driver programs written in "C" allow the experimenter to pick the parameters that determine the steering tasks the STI sub-system displays to the user and the parameters that determine the steering mode experienced by the user. Also, this computer is used to record the signals from the position and force sensors and update the torque setting to the motor via a motion control board and a power amplifier.

The two computers are set-up to communicate over serial (RS 232 protocol) and digital ports. The commands for choosing the roadway scene are sent to the STI computer via serial ports and the signals to start/stop collection and stop torque control are sent to the experimenter's computer via digital ports.

The unique split steering wheel configuration, shown in Figure 2, enables the forces generated with each limb to be measured independently. The rim of the wheel is a steel tube that is split into two sections. Each half is supported by two flexible spokes that flex in the tangential direction. The tangential forces are measured by two load cells located at the base of the wheel.

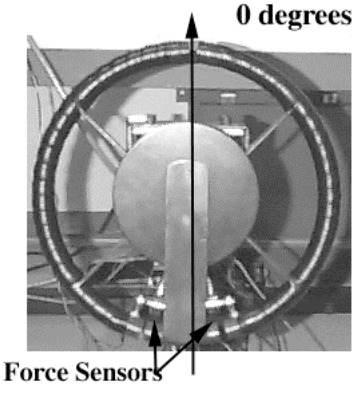

Figure 2: The split-steering wheel

Modes of Operation

Driver's SEAT is intended to be used throughout the entire recovery cycle of a subject with hemiplegia. We designed the system to be able to implement three steering modes that complement the three main recovery stages of stroke [2]. Named according to the participation of the paretic limb, the modes are passive movement (PM), active steering (AS), and normal steering (NS).

The PM mode was designed for subjects whose paretic limb is flaccid. Since they have no volitional control over their paretic limb, they are instructed to perform the steering task using their non-paretic limb. The non-paretic limb is used to begin retraining of the paretic limb. At the wheel, the weight of the paretic limb is compensated by the servo-mechanism, i.e., the paretic limb is moved passively while the non-paretic limb actively steers. This mode design was based on research [1,13] that suggests that motor recovery may be enhanced by matching up the cortical activity associated with attempting to initiate movement with proprioceptive feedback associated with that movement.

When subjects begin to demonstrate that they are regaining some volitional control over their paretic limb, they are permitted to begin exercising in the AS mode. The AS mode was designed for subjects whose paretic limb has moderate hypertonia and synergistic movement. Subjects are instructed to perform the steering task using their paretic limb, relaxing, if possible, their non-paretic limb. At the wheel, the forces exerted by the non-paretic limb are counteracted by the servo-mechanism, i.e., the paretic limb is encouraged to steer actively and the non-paretic limb is actively discouraged. This mode was designed based on the "forced-use" research.

The NS mode was designed to allow us to assess how subjects distribute their limb forces, i.e., how much the paretic limb participates in the steering tasks. The mode is also used as a general exercise mode to assess limb coordination. Typically, subjects use this mode as their primary exercise mode when their motor deficits have been minimized and “normal” voluntary control has returned. They are encouraged to practice coordinated driving and improve their force symmetry by actively steering with both their paretic and non-paretic limbs.

Control Architecture

To successfully complete a steering task on a simulator a driver is said to act as a position controller. In the context of driving, a position controller extrapolates from the displayed roadway scene a control signal (desired steering angle) that allows the vehicle to track on or within road edge lines [14]. Studies in manual control theory [e.g., 14] suggest that this position control action is intuitive and can be performed by the average human.

In the Driver's SEAT control design, users are asked to go a step further and convert their steering control signal into an equivalent torque control signal. They are asked to generate this equivalent torque signal by modifying their limb torques in a manner appropriate to the current steering mode.

The three steering modes are implemented using the proportional - derivative (PD) torque control law shown in Equation 1 where K_p and K_v are the proportional and derivative constants, respectively.

Equation 1:

$$T_{motor} = K_p(T_{actual} - T_{desired}) + K_v(T_{actual} - T_{actual-1})/\Delta t$$

T_{actual} is the actual torque on the steering wheel, $T_{actual-1}$ is the previous value of the actual torque, $T_{desired}$ is the torque command sent to the motor, and Δt is the sampling time. The desired torque is given by Equation 2.

Equation 2:

$$T_{desired} = T_{restore} - T_{resist} + T_{assist}$$

The restoring torque is defined in terms of the steering wheel angle, θ:

$$T_{restore} = T_{\max} * Sin(\frac{9}{2}\theta)$$

when $|\theta| \le \frac{\pi}{9}$ and $T_{restore} = -\frac{|\theta|}{\theta} * K_a * \theta$ when $|\theta| > \frac{\pi}{9}$, where K_a is defined so that for a given steering angle range, $T_{restore}$ does not exceed a maximum permissible torque (this torque is defined based on safety and other subjective factors). The sine function allows us to smoothly transition (±10•) between steering directions and thus maintain “road feel” at the wheel.

If the subject has left hemiplegia (left limb is paretic and the right limb is non-paretic), then $T_{resist} = F_{non-paretic} * R$ and $T_{assist} = F_{paretic} * R$. The forces ($F_{non-paretic}$ and $F_{paretic}$) are obtained from the load cells, and R is the radius of the steering wheel.

The desired torque changes with the steering modes and is used to create the interaction effects at the wheel. Again, assuming the subject has left hemiplegia, Table 1 shows how the desired torque changes.

Modes:	Desired Torque
PM	$T_{desired} = T_{restore} + T_{assist}$
AS	$T_{desired} = T_{restore} - T_{resist}$
NS	$T_{desired} = T_{restore}$

Table 1:The desired torque used in each mode.

For example, if subjects steering in the AS mode are able to modify their limb dynamics so that only their paretic limb steers then they will experience minimal resistance torques. The dominant motor torques on the wheel will be the restoring torques that give a sense of “road feel” to the task.

Experimenter/User Protocol

The Driver's SEAT system is designed to be used with subjects with right or left hemiplegia. A typical session using the system progresses as follows: The experimenter asks the subject to sit in a posture supported chair and place their hands at the ± 90° (3 and 9 o'clock) positions on the steering wheel. Their arms are placed in the following position: forearms neutral, elbows flexed to about 90 degrees and shoulders slightly abducted and flexed. The steering wheel tilt and height is adjusted to provide a comfortable interaction with the steering wheel throughout the range of motion. The experimenter describes the steering task to the subject and then begins the road scene. The subject is expected to perform the described task.

For subject safety, adjustable mechanical stops limit the rotation of the steering wheel to not exceed ±135° from neutral, and an emergency stop pedal is placed under the subject’s left foot so that power can be disconnected at anytime during a session.

Future Work

To assess the efficacy of the three operational modes, at least 8 stroke patients will be tested. We will explore whether our designed modes can encourage subjects' non-paretic and paretic limbs to interact in the ways we have proposed. Along with video data and EMG muscle group activity, we will use our measures of wheel position and bilateral limb forces exerted on the wheel to determine the success of our approach.

Acknowledgments

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