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Design and evaluation of Driver's SEAT: A car steering simulation environment for upper limb stroke therapy

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SUMMARY
Hemiplegia, affecting approximately 75% of all stroke survivors, is a common neurological impairment that results in upper and lower limb sensory and motor deficits. Recovery of coordinated movement of both upper limbs is important for bilateral function and promotes personal independence. This paper describes the philosophy and design of Driver's Simulation Environment for Arm Therapy, a one-degree-of-freedom robotic device that uses a modified Constraint-Induced therapy paradigm to promote coordinated bilateral movement in the upper limbs. Baseline force and tracking data for four neurologically unimpaired subjects who completed bilateral and unilateral steering with the impaired arm using the device are presented.

KEYWORDS: Driver's SEAT; Stroke therapy; Robotic device.

1. INTRODUCTION
The Driver's Simulation Environment for Arm Therapy (Driver's SEAT) is a prototype rehabilitation device developed at the VA Palo Alto Health Care System (VAPAHCS) Rehabilitation Research & Development Center (RRDC). Driver's SEAT tests the efficacy of patient-controlled bimanual exercise by encouraging active participation of the impaired limb of stroke survivors. Hemiplegia, affecting approximately 75% of all stroke survivors, is a common neurological impairment that results in upper and lower limbs sensory and motor deficits on the side of the body contralateral to the location of the cerebral vascular accident.[1] Driver's SEAT, one-degree-of-freedom robotic device, is a car steering simulator equipped with a specially designed steering wheel that measures the forces applied by each of the driver's upper limbs. An electric motor provides programmed assistance and resistance torques to the wheel.

2. 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[1–3] 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[5–7] and enhanced therapy[8,9] provided the most promising evidence that motor recovery can be facilitated. An awareness of how these strategies succeed in improving arm function is important to understanding the design of Driver's SEAT.

The idea of "forced-use" of the impaired limb has been introduced as a countermeasure to learned non-use. Taub[10] observed this behavioral phenomenon while he studied unilateral and bilateral deafferentation in monkeys. Deafferentation is a surgical procedure that leaves the forelimbs of the monkeys with intact efferent motor pathways but no sensory feedback. Reported in 1980, the study revealed that monkeys spontaneously compensated for their impaired forelimb when they were not motivated to use it. Thus, they developed the habit of learned non-use. Restraining the normal forelimb for at least seven days interfered with the monkey's ability to perform survival activities with their "good" forelimb and provided a motivating reason for them to use their impaired forelimb for grooming and eating tasks. Taub suggested that this behavioral phenomenon might occur with stroke survivors who, after numerous failed attempts at using their impaired limb, may also become discouraged and develop this learned non-use behavior.

Wolf *et al.*[5] successfully implemented Taub's forced-use strategies with chronic stroke survivors. More recent studies[11,12] in forced-use, subsequently termed constraint-induced movement therapy, continue to give support to the effectiveness of this therapy strategy. Chronic stroke subjects given two weeks of constraint-induced therapy experience dramatic gains in their ability to use their impaired limb in real world environments, as well as permanent neurological changes in the size and shape of the area of the motor cortex devoted to their impaired and normal arms.[12]

Enhanced therapy (or intensive therapy) is a less radical method of improving arm function and preventing impaired limb non-use.[8,9] This method usually involves modifying conventional therapy in three ways: (i) supplementing correctional condition with repetitive self-directed exercise, (ii) increasing the frequency of therapy sessions, and (iii)

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increasing the adherence to self-directed exercise with behavioral methods that encourage subjects and their families to be active participants in the therapy.

Enhanced and forced-use therapy strategies can be 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 impaired limb in exercises, and more repetitive training. Besides these elements, other variables, such as early intervention, external motivation, and bilateral exercise, have been proposed as important for successful rehabilitation outcomes. Driver's SEAT, developed as a prototype for a stand-alone or home-therapy device, incorporates many of these key components into its rehabilitation therapy strategies.

Driver's SEAT offers a unique environment for both rehabilitation therapy and assessment. It uses a traditional driving simulator to create tracking tasks in an entertaining context. Although the concept for using a driving simulator environment outfitted with a uniquely designed split-steering wheel for upper limb rehabilitation therapy is novel, the use of the steering environment as a tool to assess upper-limb sensory-motor recovery in individuals following brain damage is not. An early clinical study by Jones *et al.*[13] used a system with an instrumented steering wheel to present periodic and random preview tracking tasks to normal and impaired subjects recovering from brain damage due to head-injury or stroke. Their later study[14] used a battery of computerized tracking tasks to quantify impairment and recovery of the sensory-motor function of both limbs. Their study showed that both limbs have some degree of impairment; however, the impaired limb experiences significantly more functional loss. For this reason, we refer to the least impaired limb as the "unimpaired" limb.

The fact that driving is a motivational functional task supports the use of the Driver's SEAT environment for upper limb rehabilitation therapy. In his literature review, Katz *et al.*[15] 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 community re-integration. 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.

Transferring some of the responsibility for task success from the therapist to the stroke patient facilitates sustaining motivation throughout a rehabilitation program on Driver's SEAT. One suggested method to transfer task success is to engage subjects in patient-controlled exercises. The benefits of patient-controlled exercise are under investigation in another study[16] at the RRDC involving an upper limb assessment and therapy device called the Mirror Image Motion Enabler (MIME). In this study, a six degree-of-freedom robot is used to implement bilateral exercises (structured tracking tasks) that allow the normal limb to guide the therapy of the impaired arm. As a result, the person initiates and controls the therapy in a natural way. The level of each subject's recovery and strength determines the type of force intervention given. In the context of Driver's SEAT, patient-controlled therapy occurs when subjects influence the level of force intervention used to remind them to increase the participation of their impaired limb in bilateral steering tasks.

Driver's SEAT uses a modified forced-use paradigm to encourage persons to rely more on their impaired limb. Three steering modes are designed into Driver's SEAT to allow the impaired and normal limbs of subjects to interact in different ways. In each mode, subjects' ability to successfully complete the bilateral steering tasks is coupled to ability to modify the tangential forces generated on the steering wheel with each limb. In the main therapy mode, subjects experience a resistance of the steering wheel to movement by the unimpaired limb. The resistance is proportional to the amount of force input from the unimpaired limb. The resistance of the wheel becomes an important *force cue* that works to discourage subjects' attempts to use their stronger limb to compensate for the weaker limb during the steering task.

3. HARDWARE/SOFTWARE DESIGN

The current Driver's SEAT system (Figure 1) consists of a motor, an adjustable-tilt split-steering wheel, a height-adjustable frame, wheel position sensor (4096 count optical encoder), dual wheel-rim 1-axis load cells, Systems Technology Inc. (STI) simulation hardware,[17] and the Driver's SEAT control computer hardware. The Driver's SEAT system can quantify cognitive and sensorimotor skill recovery using both position and force related performance measures.

The split-steering wheel is shown in Figure 2; it interfaces with STI's PC-based driving simulator hardware. In real time, the STI computer generates realistic graphical road scenes and collects data 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 three-dimensional and the rate at which the roadway appears to move towards the driver is a function of speed. Several road scenes, each designed to last approximately one minute, give users the "feel" of rural, suburban, or urban driving.

Throughout this paper, steering tasks are defined according to the roadway scene and the set of verbal instructions given to the drivers to guide them in navigating the scene. Each steering task is designed such that if users: (i) follow the experimenter's instructions, (ii) keep their car icon tracking a road dividing line, and (iii) coordinate their limbs as instructed, then they are able to successfully complete the tasks. Steering tasks are implemented without user-controlled accelerating and braking in order to allow users to concentrate solely on steering and on regaining coordinated upper arm movement. Training coordinated movement between both the impaired upper limb and the lower limbs (one of which is impaired)[1] is outside the scope of the present study. Currently, the simulation software does not allow us to define steering tasks with computer-controlled

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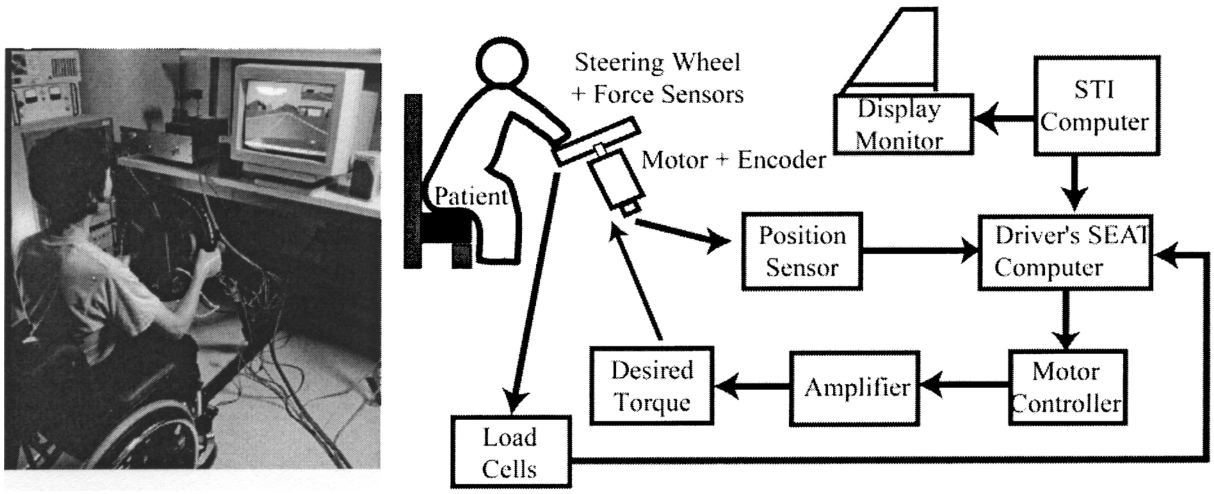

Fig. 1. A flow chart of the current Driver's SEAT System showing the relationship between the major components. The patient, seated in front of the display monitor, grasps the wheel with both limbs. The wheel, 0.37 meters in diameter, has an adjustable-tilt that ranges from 0° to 90°. The height of the adjustable frame ranges from approximately 0.56 to 1 meters. The Driver's SEAT computer samples the force and position sensors and sends via the motor controller a desired torque command to the motor that is directly attached to the steering wheel. The STI computer displays the steering task and collects relevant steering dynamic data.

adjustment of speed, so the absence of user-controlled steering meant that the apparent vehicle speed was set *a priori* and remained constant throughout the task. The apparent vehicle speed was set at 13.41 meters per second to give users the ability to turn corners at a speed that does not require braking.

On the Driver's SEAT computer, parameters are chosen to determine the steering task the STI sub-system displays to the user and 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 unique wheel configuration (Figure 2) measures the forces generated with each limb independently. The rim of the wheel is a steel tube that is split into two sections; two flexible spokes support each half of the wheel. Two load cells located at the base of the wheel measure the tangential forces, which can be used to derive objective force-based performance metrics. Recent results in upper limb rehabilitation therapy using robotic devices[18,19] support the use of forces and torques as a measure of abnormal function of the impaired limb.

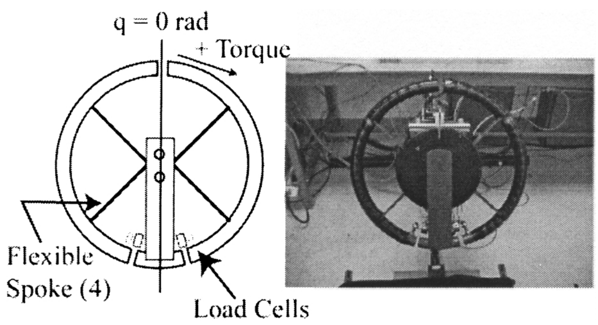

Fig. 2. A front view of the split-steering wheel. The rest position of the wheel is designated by $q = 0$ radians. Positive torque is to the right (clockwise). The load cells located at the base of the wheel detect 0.0254 mm (0.001 inch) of deflection and measure up to 225N (50lbf) of compressive or tensile tangential force generated at the wheel rim.

4. MODES OF OPERATION

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

4.1. Passive movement mode

The *PM mode* was designed for subjects whose impaired limb is flaccid. Since they have no volitional control over their impaired limb, they are instructed to perform the steering task using their unimpaired limb. The unimpaired limb is used to begin retraining the impaired limb. The servomechanism compensates for the weight of the impaired limb; the impaired limb is moved passively while the unimpaired limb steers. Bilateral rehabilitators, designed by Lum and co-workers,[20,21] provide examples for implementing force-based servomechanisms that use the unimpaired limb to help assist the impaired limb during the PM mode. These rehabilitators provide adaptive force assistance to the impaired limb.

Including this mode into Driver's SEAT was important in the face of increasing evidence correlating early stroke rehabilitation interventions to improved functional outcomes. In a recent comprehensive review of the medical literature from 1950 to 1998, Cifu *et al.*[22] found a strong positive correlation between the early onset of condition intervention, within 3 to 30 days post-stroke, and improved functional outcomes at discharge and follow-up (3 to 12 months after condition). Evidence[23] supporting functional reorganization of the brain soon after stroke also suggests a neurological benefit to an early intervention strategy. In view of these findings, the *PM mode* was implemented to provide rehabilitation therapy within the first 30 days.

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4.2. Active steering mode

When subjects begin to demonstrate some volitional control over their impaired limbs, they are permitted to begin exercising in the *AS mode*. The AS mode is designed for subjects whose impaired limbs have moderate hypertonia and synergistic movements. Subjects are instructed to perform the steering task using their impaired limb, relaxing, if possible, their unimpaired limb. At the wheel, the servomechanism is programmed to diminish the effect of forces exerted by both limbs on the wheel by counteracting tangential forces on the wheel due to the unimpaired limb (detected by the dedicated force sensor). As a result, the impaired limb is encouraged to steer while the unimpaired limb is actively discouraged.

This mode was designed to automate a modified constraint-induced therapy approach based on the works of Wolf, Taub *et al.*,[5,6] in which the normal upper limbs of chronic stroke patients were fully restrained in a hand splint and kept in a sling for 90% of a two-week interval. While the normal hand was unavailable for use, each subject was encouraged to use the impaired arm for various functional tasks. In the context of bilateral steering in the AS mode, we use force reflection to partially restrain the unimpaired limb. Partial restraint is accomplished using force cues, previously defined as the resistance of the wheel in proportion to the unimpaired limbs' tangential force on the wheel rim.

Since our implementation of the AS mode, Taub *et al.* have independently developed a variation on their initial full restraint technique that has closer correspondence to our AS mode. This restraint method[11] encases the normal hand in a cumbersome hand glove to deter its use. One important difference between the force cue reminders used by Driver's SEAT and the hand glove constraint-induced therapy strategy is in the way enforcement is managed. While performing a task, if a subject tries to use the normal hand, the bulky glove serves to remind (cue) them to not do so. If the subject ignores the reminder and attempts to use the unimpaired limb, the physical therapist intervenes with a verbal encouragement to use the impaired limb. In contrast, the AS mode force cue opposes the unimpaired limb and in doing so it automatically prevents subjects from ignoring its reminder. The maximum opposing torque subjects experience is 5.6 Nm, which is equivalent to a tangential force at the rim of 31 Newtons.

4.3. Normal steering mode

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

The goal for implementing the control strategy used in this mode was to duplicate the response of a standard car steering wheel to wheel-rim forces from both limbs. In this mode, subjects experience a light torque that opposes any movement of the wheel away from its zero degree position. It is important to note that if subjects adhere to the steering instructions given in the PM and the AS modes, they also experience this light restoring torque. The differences between the AS mode and the NS mode can be summarized in terms of the presence of force cues in the AS mode and absence of force cues in the NS mode.

5. CONTROL ARCHITECTURE

Figure 3 shows the general control flow diagram for the Driver's SEAT system. To successfully complete a steering task on a simulator, a driver is said to act as a position

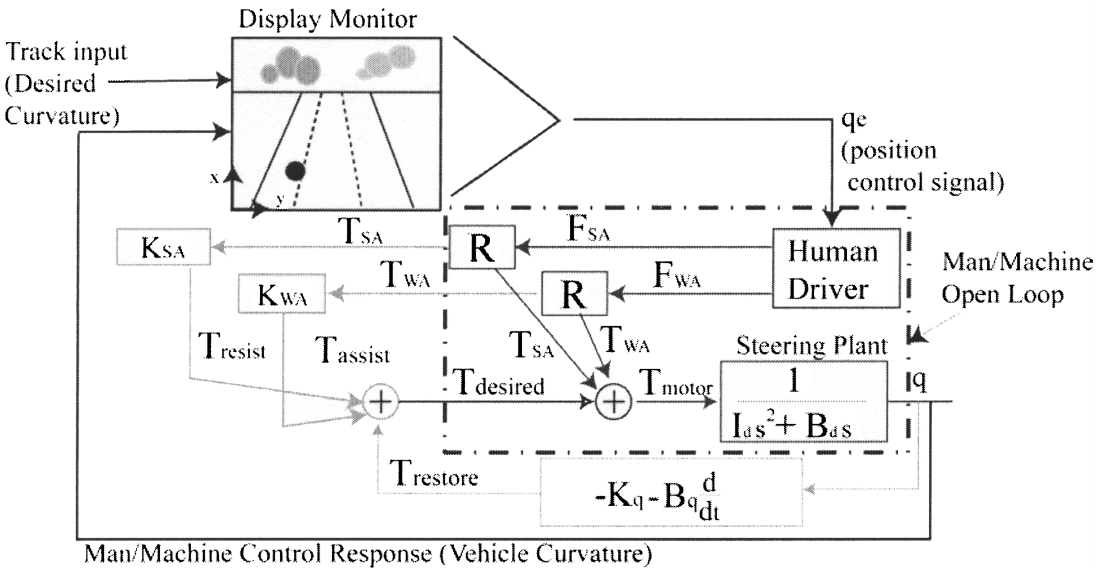

Fig. 3. The general control flow diagram for the Driver's SEAT system. The open loop system consists of the human driver and the steering wheel. The 2-tier closed loop system consists of the torque control loop, which is modeled using our general control law, and the tracking control loop, which is not explicitly modeled. The transfer function of the steering wheel plant is modeled as a continuous system where "s" is the Laplace transform operator. WA and SA, respectively, refer to the impaired arm and unimpaired limbs.

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controller. In the context of driving, a position controller extrapolates from the displayed roadway scene a position control signal (q_e) that allows the vehicle to track on or within road dividing lines. Studies in manual control theory[24] suggest that this position control action is intuitive and can be performed by the average human.

In the Driver's SEAT control design,[25] drivers with hemiplegia are asked to go a step further and convert their control signal (q_e) into an equivalent force control signal ($F_{WA}+F_{SA}$), where F_{WA} is the tangential force due to the weaker impaired arm (*WA*) and F_{SA} is the tangential force due to the stronger unimpaired arm (*SA*). Users are asked to generate the equivalent force control signal by modifying the impaired and unimpaired arms' tangential forces on the wheel rim in a manner appropriate to the current steering instructions. The torques developed about the wheel center as a result of each limb's tangential force are $T_{WA}=F_{WA}R$ and $T_{SA}=F_{SA}R$, where the moment arm, R, is the radius of the wheel. In this paper, these torques are referred to as *constraint torques*. The human plant is not explicitly modeled in this control implementation, therefore, constraint torques are treated as disturbance torques that perturb the wheel from its zero position.

Table I summarizes the version of the control law used in each of the three steering modes and Table II summarizes the parameters used in Table I and Figure 3, as well as in Equations (1) through (5). The desired torque changes with each mode and is used to create the three different

Table I. Summary of the control law used in each steering mode.

Steering Modes	Control Laws
PM	$T_{desired}=-K_q q-B_q\dot{q}+K_{WA}T_{WA}$
AS	$T_{desired}=-K_q q-B_q\dot{q}+K_{SA}T_{SA}$
NS	$T_{desired}=-K_q q-B_q\dot{q}_p$

Table II. Summary of the parameters used in Figure 3, Table I, and in Equations 1 through 6.

Control Parameter	Function	Value	Units
I_d	Wheel Inertia	0.0322	$N-m-s^2$
B_d	Wheel Damping	0.0117	$N-m-s$
K_q	Prop. Gain	1.7981	$\frac{N-m}{rad}$
B_q	Deriv. Gain	0.23	$N-m-s$
R	Wheel Radius	0.1809	m
K_{SA} (AS)	Torque Gain	0	–
K_{WA} (AS)	Torque Gain	–0.85	–
K_{SA} (PM)	Torque Gain	–0.85	–
K_{WA} (PM)	Torque Gain	0	–
K_{SA} (NS)	Torque Gain	0	–
K_{WA} (NS)	Torque Gain	0	–

interaction effects at the wheel. $T_{desired}$ is the torque sent to the motor. The general control law governing all three modes is

$$T_{desired}=-K_q q-B_q\dot{q}+K_{SA}T_{SA}+K_{WA}T_{WA}. \quad (1)$$

where q is the steering angle, K_{SA}, K_{WA} are feed-forward gains and K_q, B_q are proportional and derivative gains respectively.

In the NS mode (Table I), the restoring torque is a proportional-derivative (PD) torque control law,

$$T_{restore}=-K_q q-B_q\dot{q}, \quad (2)$$

allows both the impaired and unimpaired limbs to move the wheel.

The control laws in the AS and PM modes are similar. In the PM mode, the extra term,

$$T_{Assist}=K_{WA}T_{WA}, \quad (3)$$

added to the PD control law of the NS mode, compensates for the "dead" weight of the flaccid, impaired limb in order to assist the passive movement of the impaired limb by the unimpaired limb. On the other hand, the extra term,

$$T_{resist}=K_{SA}T_{SA}=K_{SA}(F_{SA}R), \quad (4)$$

used in the AS mode, approximates the torque from the unimpaired limb and opposes it. The result is a *force cue* that blocks the unimpaired limb from moving the wheel. The values for the gains K_{WA} and K_{SA} were experimentally set to counteract about 85% of the forces generated by the limbs. Noise and modeling errors prevented stable control at a 100% force opposition. Under unilateral steering, the PM and AS mode control equation seen in Table I reduce to the NS mode equation.

The general formulation of the control law governing all three modes is

$$T_{desired}=T_{restore}+T_{resist}+T_{assist}. \quad (5)$$

Utilizing a second-order plant model for the wheel that neglects friction with this controller, the closed-loop position response of the system becomes

$$q=\frac{(1+K_{WA})T_{WA}+(1+K_{SA})T_{SA}}{I_d s^2+(B_d+B_q)s+K_q}. \quad (6)$$

The PC-based controller, implemented in "C", uses an incremental encoder card (4096 counts per revolution) to sample the encoder signal and a data acquisition card (12-bit resolution) to sample the analog signals from the load cells and output the desired torque to the motor.

6. HYPOTHESIS

This study aims to characterize neurologically unimpaired subjects' limb interactions at the wheel and tracking performance during bilateral and unilateral steering in each therapy mode. This study provides baseline data to assist in evaluating the potential benefit of patient-controlled bimanual steering therapy for persons with hemiplegia. Specifically, data characterizing the function of the non-

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dominant limb during steering tasks provide baseline reference for the impaired limb of hemiplegic drivers.

The clinical potential of our methods depends on the ability of the diagnostic mode (NS) to detect, consistently, the presence of upper limb compensatory steering strategies and the ability of our main therapy mode (AS) to increase the level of impaired limb activity in an exercise task. As a result, we chose to concentrate on evaluating subjects' steering activities in NS and AS modes. Outcomes are quantified in terms of metrics that grade constraint torques arising from limb interactions at the wheel and tracking performance on the simulated roads.

We hypothesize that neurologically unimpaired subjects, with intact volitional control over each limb and no significant differences between their non-dominant and dominant limbs, will not have significant differences in tracking performances across all conditions, i.e. our control subjects will do equally well tracking with one or both limbs.

The learned non-use behavior described earlier for persons after a stroke does not affect how neurologically unimpaired subjects perform bilateral steering tasks in the NS and AS modes of Driver's SEAT. Hence, we hypothesize that in the NS mode, in which the wheel responds to both limbs equally, neurologically unimpaired subjects should not significantly favor the dominant limb, therefore, they should not attempt to keep it as the "controlling" limb in all tracking tasks regardless of the verbal tracking instructions given and the force cues presented.

The absence of learned non-use compensatory behavior means that in the AS mode, neurologically impaired subjects should successfully follow the instructions to maintain a relaxed posture with their dominant limb while steering with their weaker non-dominant limb. For right-handed unimpaired subjects, the mean value of the relaxed dominant limb's average torque ($\bar{t}_{SA}$) is expected to be positive, less than the absolute mean value of the impaired limb's average torque ($|\bar{t}_{WA}|$), and have a small standard deviation. We hypothesize that the level of participation of non-dominant limb in the AS-bi condition, as quantified by the average torque levels, will increase significantly over the NS-bi condition.

7. METHODS

A typical experimental session using the system progresses as follows: The subject's impaired limb is prepared with surface electrodes to monitor muscle activity during steering. Subjects sit in a chair that limits trunk motion and place their hands at designated positions (approximately $\pm\frac{\pi}{2}$ radians or $\pm\frac{\pi}{4}$ radians) on the steering wheel. Their arms are placed in the following position: forearms neutral, elbows flexed to about $\frac{\pi}{2}$ radians 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. For subject safety, adjustable mechanical stops limit the maximum rotation of the steering wheel to ±2.4 radians from neutral, and an emergency stop pedal is accessible to the subject's normal foot so that power can be disconnected at any time during a session. During this session, opposing torques, our force cues, were limited to 4.5 Nm.

Table III. Summary statistics on four normal subjects.

Subject	Gender	Age	Strong Arm (SA)
LN1	M	72	R
LN2	F	68	R
LN3	M	61	R
LN4	F	52	R

A total of four neurologically unimpaired subjects who reported a right-hand dominance participated in this portion of the study. Table III lists the characteristics of these control subjects (LN1–LN4). Subjects were asked to complete four sessions of seven randomly presented steering tasks. The goal of the 50-second preview tracking task was to keep a spot representing the lateral movement of the simulated car on the display monitor superimposed on a lane's dividing line (track), appearing to the right of the spot (refer to display monitor illustrated in Figure 3). Subjects could preview the track's contour ahead of its current longitudinal position.

The contour of the desired track, specified in terms of curvature (ρ in m^{-1}), is given by

$$c_d(t)=\begin{cases}\rho=0 & 0\le t<5 & \\ \rho=0.001 & 5\le t<20 & \text{Right (RT)}\\ \rho=0 & 20\le t<35 & \text{Straight (ST)}\\ \rho=-0.001 & 35\le t<45 & \text{Left (LT)}\end{cases}. \tag{7}$$

The first five seconds of the track is removed and only the 45 seconds pertaining to the subtasks are considered. The track contains three distinct curvatures, right turn subtask (RT) (ρ=0.001 m^{-1}), straight segment subtask (ST) (ρ=0 m^{-1}), and left turn subtask (LT) (ρ=−0.001 m^{-1}), which define the three subtasks. Only the middle 9 seconds of each steady-state tracking portion, RT(ss), LT(ss), and ST(ss), are used to evaluate tracking performance. Steering the desired track required rotating the steering wheel approximately $\pm\frac{\pi}{6}$ radians, however the mechanical stops were set to permit subjects to move the wheel through the angular range of $\pm\frac{\pi}{4}$ radians.

The NS and AS modes paired with bilateral (*bi*) and unilateral steering with the WA to create four test conditions, NS-bi, AS-bi, NS-WA, and AS-WA, k=1, 2, 3, 4 respectively. As a result of the four sessions, each subject (j=1, 2, 3, 4) experienced each condition four times, leading to four trials (i=1, 2, 3, 4). For the NS-bi condition, subjects were instructed to steer with both limbs. For the AS-bi condition, control subjects were instructed to steer with the non-dominant limb and keep the dominant limb grasping the wheel but relaxed; and for the NS-WA and AS-WA conditions, control subjects were instructed to steer with WA while keeping their dominant limb in their lap.

A video record was made of each session. Force data, steering angle position, and calculated steering angle velocity were sampled at 300 Hz. The STI computer also sampled steering angle position (at the slower rate of 10 Hz); this data was used by the STI system to calculate vehicle curvature (subject's response to the track, c) as well as lateral position, velocity, and acceleration. (Note: The equations used to calculate these kinematic relationships are provided in the STI manual).[17]

These subjects were considered potential age-matched controls for the left-side impaired stroke subjects, who are older than 50 years. Our test protocol was approved by Stanford University's Institutional Review Board. All subjects signed an informed consent.

8. RESULTS AND DISCUSSION

Torque and tracking results for bilateral steering and unilateral steering with the impaired limb in the NS and AS modes are reported and discussed below. Due to a problem with one subject's data from the first trial, only the data sets from three trials are included in the analysis.

In our analysis, we used parametric statistical methods,[26] i.e. the repeated measures ANOVA, to detect significant effects of the four conditions on subjects' tracking performance and limb constraint torques. The Tukey/Kramer post hoc test[26] was used to assess alpha level of 0.05 (significant if $p<0.05$). A comparison between the two modes tests the effect of the force cue intervention on tracking performance, or limb interaction at the wheel.

8.1. Tracking performance

In each condition, k, and each trial, i, a subject's control response resulted in a vehicle tracking profile. Vehicle tracking profiles, averaged across all three trials, produced an average tracking profile per condition, c_a. Figure 4 presents a typical subject's average tracking profile for each condition. A 95% confidence interval is plotted along with the average tracking profile. From the resulting average vehicle and desired track profiles, c_a and c_d, respectively, we calculated root means square (RMS) of the steady-state tracking error (c_e) for all three subtasks ($m=1, 2, 3$), for each subject ($j=1, 2, 3, 4$), and for all four conditions ($k=1, 2, 3, 4$).

According to Poulton,[27] the defining feature of a preview task is the ability to see both the spot and the movement of the track. A subject's ability to manage this feature will influence tracking performance. Tracking performance depends on the subject's ability to modify the control response, q_e, given preview knowledge of the track and the relative position error between the spot's current lateral position and that of the track. The RMS error,[26] vertical distance between the track and the subject's response, provides an adequate measure of tracking performance. Low RMS errors typify good tracking performance.

Subjects' steady-state tracking performances for the NS (no force cues) and AS (with force cues) modes are graphically presented in Figure 5. Figure 5a graphically illustrates each subject's bilateral and unilateral tracking performance for the two modes while Figure 5b illustrates the combined tracking performance of all four subjects. We calculated the combined tracking performance scores for the NS and AS modes by averaging steady-state RMS errors across all subjects and across all subtasks.

According to Figure 5a, three of the four control subjects (LN1, LN2, and LN4) had no significant differences ($p>0.05$) in non-dominant limb tracking between modes, i.e. the RMS scores for AS-WA and NS-WA were similar. Also, there were no significant differences in subjects' tracking performances for bilateral tracking in AS-bi condition and either bilateral tracking in NS-bi or impaired limb tracking in NS-WA and AS-WA. Their tracking performances did not appear to deteriorate with the force cue intervention. As expected, since in the AS mode the presence of force cues modified the influence of the dominant limb on the steering wheel, subjects who were able to control each limb, i.e. who were able to independently relax the dominant limb according to the steering instruction, had a tracking performance similar to non-dominant limb only tracking.

Two of the four subjects (LN1 and LN2) had large standard deviations, which tended to minimize the difference between their average RMS errors for NS-WA, AS-WA and NS-bi conditions. This result suggests that these neurologically normal subjects had less control over their non-dominant limb. This difference could be rooted in the fact that these subjects were the oldest members of our subject pool.[28]

Figure 5b shows that as hypothesized, across and within modes, control subjects did not exhibit significant tracking differences between non-dominant limb tracking and tracking with both limbs. Given our small subject size and RMS

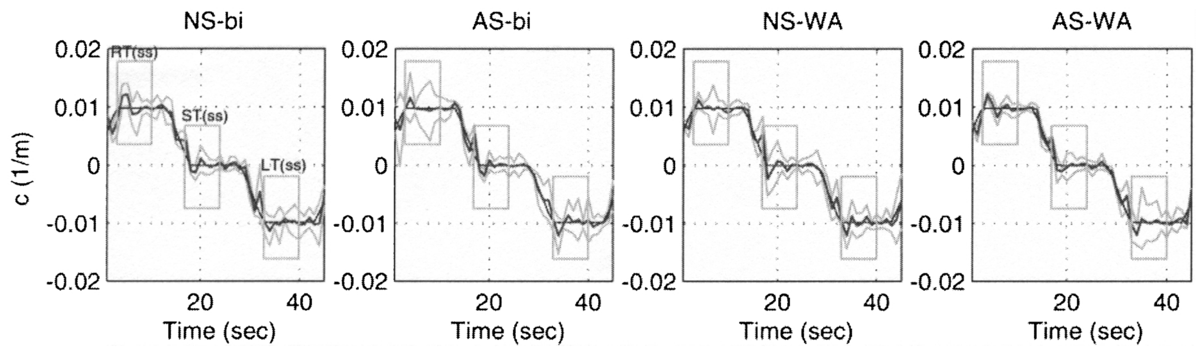

Fig. 4. A typical subject's average tracking profile for each treatment. A 95% confidence interval is plotted along with the average profile.

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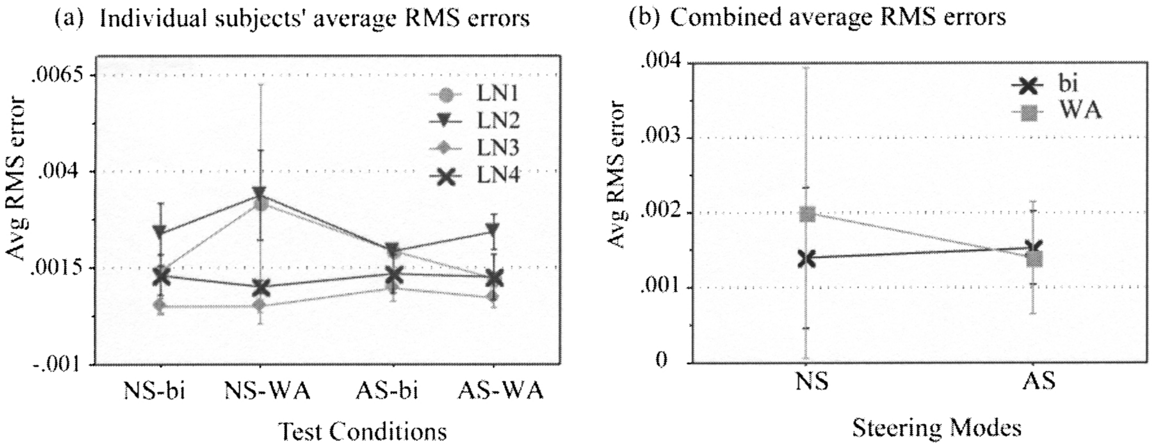

	Mean	STD.
NS-bi	.0014	.0009
NS-WA	.0020	.0019
AS-bi	.0015	.0005
AS-WA	.0014	.0007

Fig. 5. (a) shows the average RMS scores for steady-state tracking for all four subjects in all four conditions. The error bars indicate ±1 standard deviation; (b) shows a graphical summary of the combined steady-state tracking scores for the NS and AS modes. The error bars indicate ±1 standard deviation.

error values, we cautiously conclude that these results support our control design.

8.2. *Limb interaction torques*

For each condition, the non-dominant and dominant limbs' force data from each trial were converted to equivalent torques and averaged at each time point across 3 of 4 trials. For each subject, a set of average torques for the 50 second steering task, ${}^{jk}\bar{T}=[{}^{jk}\bar{\tau}_{WA}\ {}^{jk}\bar{\tau}_{SA}]^{T}$, defines how the dominant (SA) and non-dominant (WA) limbs interacted during a test condition.

The four test conditions led to three distinct relationships. Figure 6 shows a typical example of the limb interaction patterns that emerged. The average profile is shown along with traces from each of three trials. Notice that unilateral steering in both modes resulted in one distinct pattern. Since the relationship between limb torques varied according to the steering subtask, ${}^{jk}\bar{T}$ for each condition was divided into the three subtasks $m(=1, 2, 3)$, ${}^{jkm}\bar{T}=[{}^{jkm}\bar{\tau}_{WA}\ {}^{jkm}\bar{\tau}_{SA}]^{T}$. Corresponding to the tracking performance analysis strategy, only the middle 9-seconds of the steady-state portion of each subtask was used to evaluate the limb interaction results. Note that if a limb is in "control" of the steering task, it will be the limb with the greater absolute mean torque value, e.g., $|\overline{\tau_{SA}}|>|\overline{\tau_{WA}}|$.

To facilitate within and between subject comparisons across conditions, the means and standard deviations for ${}^{jkm}\bar{T}$ were calculated. These values define a subject's dominant and non-dominant limbs' torque efforts in each subtask for each condition. Figure 7 graphically illustrates the limb torques for control subjects, LN1–LN4, in the RT(ss) and LT(ss) subtasks for the NS (no force cue) and AS (force cue) conditions. The corresponding torques are listed in Table IV.

According to Figure 7, in the subtask RT(ss) in condition NS-bi, all four subjects used the dominant limb to control steering. Therefore, the absolute mean values of the dominant limb, $|\overline{{}^{jkm}\tau_{SA}}|$, were significantly greater than those of the non-dominant limb, $|\overline{{}^{jkm}\tau_{WA}}|$. In contrast, in the subtask LT(ss), 3 of the 4 subjects used the non-dominant limb to control steering. The results indicate that the two subtasks resulted in two different steering strategies. These results support the assertion that compensatory behaviors do not exist in neurologically unimpaired subjects. Most subjects were adaptable.

In the subtask RT(ss) in condition AS-bi, the level of participation of the WA limb in the AS-bi condition did significantly increase over the NS-bi condition for all four subjects. The WA limb was in control of the steering in this subtask. Since the WA limb was already in control of the steering in the LT(ss) subtask, the effect of AS-bi condition was not dramatic. Two of the four subjects had significantly increased the average torque effort of their WA limb. This result indicates that neurologically unimpaired subjects are able to practice bilateral steering that requires them to deliberately choose to use the WA limb more than the dominant limb. Although subjects such as LN1 had difficulty with the task, i.e. they could not follow the AS-bi

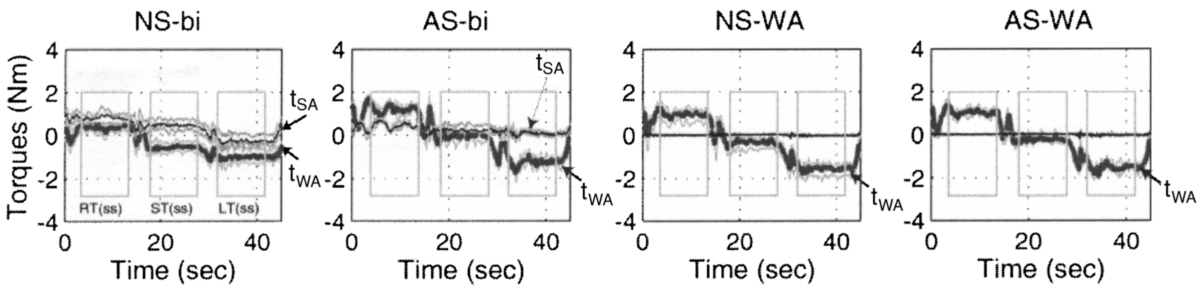

Fig. 6. Examples of the limb interaction patterns that emerged per treatment. The torque average profile is shown along with traces from each of three trials. Notice that NS-WA and AS-WA treatments result in one distinct pattern. The relationship between average torques varies according to the subtask.

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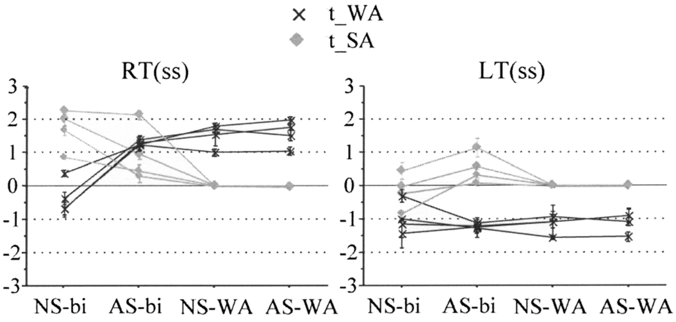

Fig. 7. Plots of the non-dominant and dominant limb average torques for the RT(ss) and LT(ss) subtasks for each subject (LN1–LN4) generated during bilateral and unilateral steering in the NS and AS modes. The thicker lines represent the non-dominant torque mean values. Error bars represent ±1 standard deviation.

instructions and relax their dominant limb throughout the subtasks, an increase in the WA limb torque efforts is still possible.

In general, we discovered some important factors that limited our ability to make strong assertions about right-handed neurologically unimpaired subject performance on Driver's SEAT. These factors are as follows:

1. Our small subject size did not allow us to strongly support our hypotheses.
2. Variations in the performances of our elderly population revealed that we might not be able to fully characterize the neurologically normal "profile" for tracking performance and limb interactions on Driver's SEAT.
3. Variations in the subjects' performance in the NS-bi condition revealed that we needed to control for subjects' current driving strategies.

9. CONCLUSIONS

The steady-state tracking performance data for our "typical" right-handed control subject indicate that neurologically unimpaired subjects have no significant differences between tracking performance across all four modes. The data also indicated that right-handed control subjects might have poor tracking performances during non-dominant limb tracking in both the diagnostic and main therapy modes. In follow-on studies that compare bilateral steering performance data across stroke and neurologically unimpaired populations, we expect that left hemiplegic subjects will differ from these age-matched control subjects. In the face of learned non-use and the tendency of stroke survivors to compensate for their lack of ability in the impaired limb with the unimpaired limb, we expect their tracking performance to be best in the NS-bi condition. The RMS tracking scores for a stroke subject who is heavily compensating for the impaired limb with the unimpaired limb should indicate significantly lower tracking error in bilateral steering in the diagnostic mode than in any unilateral, impaired-limb steering mode.

In summary, a subject's tracking performance data across conditions may be a good method for detecting compensatory tracking strategies in the NS mode. If we assume that impaired limb tracking between modes NS and AS is not significantly different, and if tracking performance is the

Table IV. The mean values for non-dominant and dominant limb average torques in the steady-state portions of subtasks RT and LT for all the four subjects. The table includes the average torques across all subjects. These data correspond to the plots in Figure 7.

	LN1		LN2		LN3		LN4		LNs (avg)	
RT(ss)	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
NS-bi, t_WA	–.685	.184	–.686	.243	.377	.107	–.377	.189	–.343	.473
NS-bi, t_SA	2.235	.123	1.993	.216	.829	.063	1.658	.168	1.679	.553
AS-bi, t_WA	1.223	.161	1.283	.213	1.225	.185	1.380	.083	1.278	.179
AS-bi, t_SA	2.110	.144	.936	.141	.443	.172	.277	.168	.941	.734
NS-WA, t_WA	1.785	.101	1.529	.338	.986	.111	1.697	.105	1.499	.365
NS-WA, t_SA	–.023	.009	–.013	.028	–.0002	.008	–.039	.011	–.019	.021
AS-WA, t_WA	1.954	.120	1.747	.237	1.044	.127	1.494	.152	1.560	.378
AS-WA, t_SA	–.052	.012	–.024	.034	.005	.009	–.032	.012	–.026	.028
LT(ss)	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
NS-bi, t_WA	–1.453	.436	–1.171	.382	–1.003	.043	–.322	.189	–.987	.516
NS-bi, t_SA	.428	.256	–.031	.218	–.254	.051	–.850	.098	–.177	.493
AS-bi, t_WA	–1.264	.290	–1.224	.194	–1.267	.161	–1.137	.154	–1.223	.214
AS-bi, t_SA	1.126	.273	.552	.081	.070	.071	.302	.086	.513	.422
NS-WA, t_WA	–1.078	.206	–1.102	.497	–1.573	.067	–.929	.143	–1.171	.370
NS-WA, t_SA	.002	.026	–.015	.049	–.029	.015	.015	.018	.007	.034
AS-WA, t_WA	–.918	.198	–.891	.209	–1.540	.135	–1.097	.135	–1.112	.312
AS-WA, t_SA	–.018	.023	.003	.035	–.031	.020	.009	.022	.009	.030

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same for NS-WA, AS-WA and NS-bi, we should be able to conclude two things. First, the impaired limb is functioning similarly in all three conditions and second, the unimpaired limb in the NS-bi condition is not compensating for the impaired limb in an unusual way. However, if the tracking performance is significantly better for NS-bi than for impaired limb tracking, then there is a strong possibility that the unimpaired limb is compensating for the lack of ability of the impaired limb. Since the impaired limb of a neurologically unimpaired subject is intact, we had expected tracking scores in NS-WA and AS-WA to be the same as those in the NS-bi condition. This was shown to be true for two of the right-handed neurologically unimpaired subjects.

Most subjects tested were able to adapt their steering strategy to the subtask demands. The controlling limb changed depending on the subtask. Combining this result with the fact that chronic stroke subjects may have learned non-use behaviors, we can hypothesize how left hemiparetic subjects' limbs may interact in the NS-bi condition. Left hemiparetic subjects are expected to demonstrate similar steering strategies as right-handed unimpaired subjects in the RT(ss) subtask of the NS-bi condition. However, in the LT(ss) subtask of the condition NS-bi, we expect that, unlike the unimpaired subjects, subjects with left hemiplegia will not want to adapt their steering strategies from the RT(ss) subtask. We hypothesize that the unimpaired limb of left hemiplegic subjects will be in "control" of the steering task for both the RT(ss) and the LT(ss) subtask.

Our neurologically unimpaired subjects were able to practice bilateral steering that required them to deliberately choose to use the non-dominant limb more than the dominant limb. Although they may have had difficulty with the task, they still increased their non-dominant limb torque efforts. In view of this, we can tentatively suggest that in the AS-bi mode, subjects with hemiplegia may show increased use of the impaired limb even though they may have compensatory behaviors and desire to control bilateral tasks with their strong limb.

Since this study demonstrated that we were able to accurately measure the constraint torques from each limb, we anticipate that our NS mode will be able to detect evidence of compensatory behaviors from the way a stroke subject's limbs interact with the wheel during bilateral steering. We also anticipate that our AS mode can increase the level of participation of the impaired limb of stroke subjects in bilateral steering.

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GLOSSARY

General Variables

sEMG	Surface Electromyographical signals
PM	Passive Movement mode
AS	Active Steering mode
NS	Normal Steering mode
CI:	Constrained-Induced therapy
RT	Right turn subtask
RT(ss)	Steady-state portion of the right turn subtask
ST	Straight segment subtask
ST(ss)	Steady-state portion of the straight segment
LT	Left turn subtask
LT(ss)	Steady-state portion of the left turn subtask
WA	Weak arm (non-dominant limb of control subjects or impaired limb of hemiplegic persons)
SA	Strong arm (dominant limb of control subjects or unimpaired limb of hemiplegic persons)
NS-bi	Bilateral steering in NS-mode (Test condition 1)
AS-bi	Bilateral steering in AS mode (Test condition 2)
NS-WA	Unilateral steering with impaired limb in NS mode (Test condition 3)
AS-WA	Unilateral steering with impaired limb in AS mode (Test condition 4)
RMS	Root means square

Control Law Variables

q	Steering angle (rad)
q_d	Desired steering angle (rad)
$\dot{q}$	Steering velocity (rad/s)
q_e	Steering angle control signal (rad)
F_{WA}, T_{WA}	Impaired or non-dominant limb tangential force (N) equivalent torque (Nm)
F_{SA}, T_{SA}	Unimpaired or dominant limb tangential force (N) and equivalent torque (Nm)
$T_{restore}$	Restoring toque in the NS mode (Nm)
T_{assist}, T_{resist}	Compensation and Force cue terms the PM and AS modes (Nm)
K_p, K_d	Proportional and derivative gains on the restoring torque of the NS mode
K_{SA}, K_{WA}	Gains on the feed-forward terms in the AS and PM modes, respectively

Other Variables

$\lvert\overline{\bar{\tau}_{WA}}\rvert$	The impaired limb's average torque (Nm)
ρ	Curvature (1/m)
k, j, i, m	Indices for test conditions, subjects, trials and subtasks, respectively
$c_a(t)$	Average vehicle tracking profile (1/m)
$c_d(t)$	Desired track (1/m)
$c_e(t)$	Tracking error (1/m)
${}^{jk}\bar{T} = [{}^{jk}\bar{\tau}_{WA}\ {}^{jk}\bar{\tau}_{SA}]^{\mathrm{T}}$	Average torque limb torques for a 50-second steering task
${}^{jkm}\bar{T} = [{}^{jkm}\bar{\tau}_{WA}\ {}^{jkm}\bar{\tau}_{SA}]^{\mathrm{T}}$	Average torque limb torques for a 9-second subtask

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