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Short paper

Design of robot assistance for arm movement therapy following stroke

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Abstract—This paper describes the mechanical and control design of a robotic device for providing therapeutic assistance to arm movement following stroke. The device uses a single motor and a passively oriented linear constraint to allow patients to reach across their workspace. Experimental evaluation of two controllers for assisting in reaching is presented.

Keywords: Rehabilitation; medical robotics; movement; muscle control.

1. INTRODUCTION

Stroke is a leading cause of long-term disability in industrialized nations. For example, in the US, over 500 000 people per year experience a new stroke and over 2 000 000 people are chronically disabled as a result of stroke [1]. Common consequences of stroke are loss of arm movement, hand dexterity and walking ability.

The number of people experiencing stroke is expected to increase in many countries. The incidence of stroke doubles with each decade after 55, and many industrialized countries such as the US and Japan have an increasing number of people over age 55. Surprisingly, little technology is currently available to treat movement impairment after stroke, even though many rehabilitation techniques are

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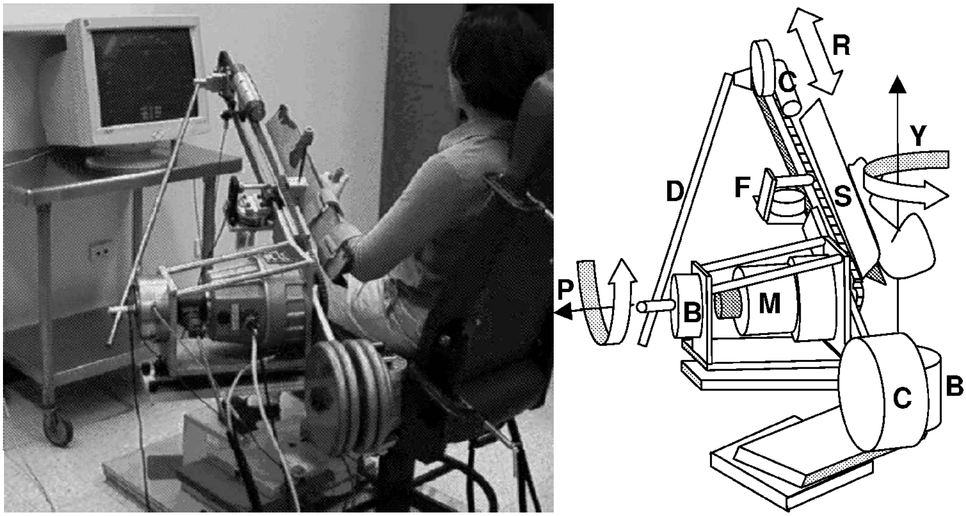

Figure 1. The ARM Guide. Left: the subject moves her arm along the device and receives visual feedback about the orientation of the device. Right: details of the mechanical structure of the device. S: splint; M: motor; B: brake; F: force/torque sensor; C: counterbalance. The three d.o.f. of the device are R: reach (actuated by the motor through a chain drive), Y: yaw (actuated by a brake) and P: pitch (actuated by a brake). The rod D provides passive compliant control of the pitch motion of the device when the pitch brake is locked.

mechanical in nature, and automation of these techniques could reduce medical costs and improve access to therapy.

To address these needs, there is increasing interest in developing robotic and mechatronic devices (or 'rehabilitators', see Table 1) for physical rehabilitation following brain injury [2]. Devices are under development for therapy of both the lower [3–7] and upper [8–13] extremities.

This paper describes the mechanical and control design of a rehabilitator for providing therapeutic manipulation of the arm following stroke. There are many possible arm therapy techniques that could be automated by robotic devices [14]. The rehabilitator described here, called the 'Assisted Rehabilitation and Measurement Guide' (ARM Guide; Fig. 1), was designed to implement a technique called 'active assist therapy' in which the device completes a desired movement for the patient if the patient is unable. In this paper, the rationale for applying active assist therapy with a rehabilitator is discussed first, followed by the mechanical and control design that implements the therapy.

2. RATIONALE FOR ACTIVE ASSIST THERAPY

The rationale for implementing active assist therapy with a rehabilitator is as follows (see also [15]). Patients with chronic brain injury typically suffer from three key motor impairments: inability to sufficiently activate the muscles needed to move

Table 1.
Rehabilitation terminology used in this paper

Term	Definition
Stroke	Brain damage due to blockage or breakage of a blood vessel in the brain. Both neural movement control circuits and communication lines are typically damaged.
Rehabilitator	A robotic or mechatronic device that physically attaches to a patient to assist in physical rehabilitation of movement.
Active assist therapy	A physical rehabilitation technique in which the therapist manually assists in completing a desired movement for the patient if the patient is unable.
Tone	The force resisting imposed movement of a limb. This resisting force arises due to the intrinsic stiffness of muscles and soft tissue surrounding a joint, and, in some cases, due to activation of muscles resisting the imposed movement.
Agonist muscle weakness	Loss of force generating ability of agonist muscles, due primarily to destruction of control circuits and communication pathways to those muscles, but also due to muscle atrophy.
Abnormal muscle synergy	A loss of directional force control in the arm, due to coactivation of muscles in rigid, or stereotypic patterns. The arm flexion synergy is characterized by simultaneous elbow flexion, shoulder abduction, and shoulder external rotation. The arm extension synergy is characterized by simultaneous elbow extension, shoulder adduction, and shoulder internal rotation (see [10, 17]).

the arm (‘agonist muscle weakness’), increased resistance to passive movement of the arm (‘increased tone’) and loss of directional force control (‘abnormal muscle synergies’) (see Table 1 for expanded definitions). Active assist therapy is designed to address the first two of these impairments by interleaving two types of exercise — repetitive movement exercise and passive range of motion exercise. Repetitive movement exercise refers to repetitive effort by the patient to initiate and control movement. This exercise allows the patient to practice activating damaged motor pathways, potentially improving the efficacy and reliability of those pathways, and thus improving agonist muscle strength. Passive range of motion exercise refers to repetitively extending shortened soft tissues. This exercise helps keep soft tissues compliant and thus can potentially reduce increased tone [16].

How does active assist exercise address the third key impairment — abnormal muscle synergies (i.e. loss of directional force control)? Stroke patients often exhibit stereotypical coupling of movement at different joints, such that they do not produce a net hand force in the desired movement direction [10, 17] (see Table 1). A potential problem with active assist therapy is that mechanically completing a movement for a patient may encourage use of these abnormal muscle synergies since the person may develop more force for reaching when using the synergies, and since any misdirected forces will be counteracted by the mechanical guidance. In the clinic, a therapist can address this problem by grading the amount of manual guidance given during arm movement. With less guidance, the patient's arm will deviate more from the intended path and the patient will receive visual feedback of their directional force error. The approach taken with the device in this paper is similar. The device incorporates a passive compliance for guiding movement. If the patient exerts a misdirected force, the compliance allows the hand to deviate a controlled amount from the desired path. The patient is thus provided with visual feedback of off-axis force generation. This visual feedback in turn provides a means for the subject to practice developing coordinated movement. Incorporation of compliance (through impedance control) has also been advocated, primarily for safety reasons, in the design of the MIT-MANUS arm rehabilitator [9].

3. MECHANICAL DESIGN

Reaching was chosen as the target arm movement task for active assist therapy with the ARM Guide, since it is fundamental to many activities of daily living. Also, an exploitable feature of reaching movements is that they typically follow approximately straight-line trajectories. This feature allowed use of a motorized linear bearing, along with two passively controlled d.o.f., to allow assisted reaching in a variety of directions. The passively controlled d.o.f. incorporate passive compliances in order to inform subjects of off-axis force generation during reaching. The resulting design is simpler than rehabilitator designs with multiple active d.o.f. [9, 11], while still achieving active-assisted reaching across the patient's workspace.

To use the ARM Guide, the patient's forearm and hand is attached to a specially designed splint that slides along the linear constraint (Fig. 1). To apply force to the arm, a motor drives a chain drive attached to the splint. Measurement of arm position is achieved by an optical encoder attached to the motor. Measurement of forces generated by the arm is provided by a six-axis load cell mounted between the splint and the linear constraint.

The orientation of the ARM Guide can be manually changed in the vertical and horizontal planes, and locked with computer-controlled magnetic particle brakes, allowing reaching at different pitch and yaw angles (Fig. 1). Also, the device is mounted on a telescoping stand for height adjustment and can be flipped to measure reaching with the left or right hand. The device is counterbalanced such that the hand splint remains at any position and orientation in which it is placed along the linear constraint, at any pitch angle. As a result, the patient experiences no static loading of the arm due to the weight of the device.

To provide feedback of abnormal muscle synergies, passive compliances were built into the ARM Guide in the yaw and pitch directions. In the yaw direction, an elastic cable chain is attached between the magnetic particle brake and the linear guide. In the pitch direction, a stainless steel rod connects the magnetic particle brake to the linear guide (Fig. 1). Compliance is provided respectively by the compliance of the cable chain (compliance = 0.09 Nm/deg) and steel rod (compliance = 0.14 Nm/deg). The optical encoders that measure yaw and pitch rotation are attached to the linear constraint rather than directly to the magnetic particle brakes. They thus accurately measure the orientation of the constraint, which varies even when the brakes are locked due to the embedded compliance.

A visual display was designed that provides a desired target window for yaw and pitch, and shows the actual yaw and pitch angles to the subject as he or she reaches (Fig. 1). In addition, the size of the cursor marking the actual yaw and pitch angles indicates how far the patient has reached along the ARM Guide.

4. CONTROLLER DESIGN AND EVALUATION

4.1. Control law 1: counterpoise assistance

At the onset, our design goal for the active assistance therapy controller was that it should allow patients to reach across their full workspace under as much of their own control as possible. One approach to achieve this goal is to compensate for any passive forces resisting movement of the arm, including gravity and the tone of the arm, and thus to allow patients to use any residual force generating ability to move. Such *counterpoise control* is an enhanced version of two common clinical devices — the mobile arm support and the overhead sling [18]. These devices counteract the effects of gravity, and allow weakened patients to practice initiating and controlling arm movement. Counterpoise control extends the action of these devices by also counteracting the tone of the subject's arm.

Implementing counterpoise control with the ARM Guide is straightforward. With the device locked in a particular yaw and pitch configuration, the force resisting movement of the relaxed arm can be measured during slow movement out and back along the linear constraint. The measured 'restraint force' is the sum of gravity and friction forces, as well as the tone of the arm. The motor can then apply an equal and opposite assist force to counteract the restraint force as a function of position (Fig. 2). The measured resisting force exhibits a hysteresis, due to friction forces in the ARM Guide and friction-like forces in the arm muscles and joints. We chose to average this hysteresis and counteract the mean resisting force as a function of hand position. Thus the patient experiences approximately the same, reduced force resisting movement during both reach (i.e. outward) and return (i.e. inward) movements, regardless of the orientation of the device with respect to gravity or the amount of tone in the arm.

4.1.1. Evaluation of counterpoise assistance. The counterpoise controller was tested with three stroke patients in order to evaluate its efficacy in assisting arm movement. Subjects A, B and C were aged 54, 71 and 32, respectively, and were 4, 21 and 2 years post stroke. Each subject had reduced active range of motion during unassisted reaching along the ARM Guide. Subjects provided informed consent, and approval for all experiments was obtained from the UC Irvine Internal Review Board.

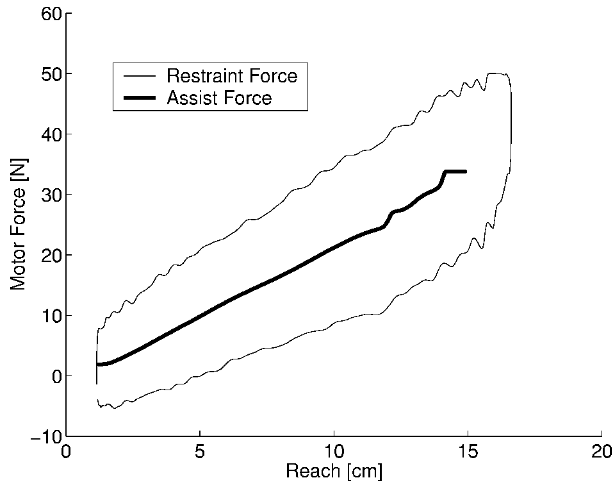

Figure 2. Implementation of counterpoise control. The arm is slowly stretched out and back along the ARM Guide to measure the restraint force, which is the sum of gravity, tone and friction forces. The assistance force is calculated as the mean of the restraint force.

Reaching with counterpoise assistance was tested in two directions (±22.5° yaw, with the device in 20° pitch). To identify the forces resisting movement of the arm, subjects were instructed to relax, and the guide moved the arm slowly out and back, through its full passive range of motion, 4 times. The mean torque applied by the motor as a function of arm position for the last trial was entered into a computerized look-up table with a resolution of 1 cm. The last trial was used because of possible relaxation of the arm with stretching [19]. For counterpoise control, the table was accessed at 100 Hz based on sensed arm position and the corresponding motor torque was applied. Subjects reached as far as possible at a self-selected speed 16 times in each direction. Counterpoise assistance was provided on eight randomly selected reaches.

For all three subjects, counterpoise assistance significantly improved active range of motion (Fig. 3). The average improvement across subjects was 3.9 ± 1.1 cm (mean ± SD, $P < 0.05$, t-test). However, none of the subjects were able to reach fully through their available passive range of motion with counterpoise assistance (mean distance remaining $= 8.1 \pm 3.2$ cm).

To better understand why subjects could not move through their full range even with assistance, the dependence of force generation on arm configuration was evaluated. First, the force required to counteract the arm restraint force at the maximum unassisted reach was estimated using the measured restraint force at the mean unassisted reach (Point A, Fig. 4). Then, the force required to overcome tone at the maximum reach with assistance was estimated, based on the measured tone minus the assisting force (Point B, Fig. 4). Using points A and B, the mean decrement in force generation with arm extension was estimated ($\mathrm{d}F/\mathrm{d}x$, Fig. 4).

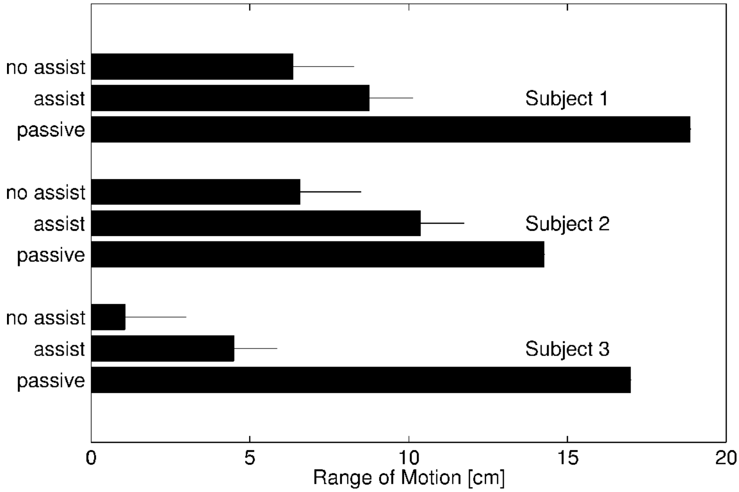

Figure 3. Effect of counterpoise assistance. The average range of motion for assisted and unassited reaching is compared with each subject's passive range of motion. For this data, the ARM Guide was locked in an orientation of +22.5° yaw (i.e. shoulder externally rotated) and 20° pitch from horizontal. Bars indicated 1 SD.

Figure 4. Procedure for estimating decrement in force generation with elbow extension. The abcissa value for Point A is the mean maximum unassisted reach for the subject. The ordinate value for Point A is the corresponding measured restraint force at the maximum unassisted reach. Thus, Point A indicates the force required to overcome tone and gravity at the maximum unassisted reach. Similarly, Point B indicates the force required to overcome tone and gravity at the maximum reach achieved *with* assistance. The estimated decrement in force generation with elbow extension is the slope (dF/dx) of the line connecting A and B.

The three subjects experienced respectively on average a 17.6, 13.1 and 16.5%/cm drop in force generation as they moved beyond the unassisted maximum range.

A possible explanation of this steep drop in strength with arm extension is a reduction in the moment arm of elbow extensor muscles with elbow extension.

However, biomechanics data indicate that the moment arm at the elbow of the primary elbow extensor, the triceps, does not decrease with increasing elbow extension [20]. Another possibility is antagonist muscle co-activation, yet this is unlikely because previous diagnostic measurements with the ARM Guide indicate that antagonist co-activation is typically not excessive at the end of the active range of motion [21]. Other possible causes of the drop in strength are altered muscle force-length properties and position dependent agonist muscle inhibition.

Regardless of the mechanism, the steep drop in strength with elbow extension limits the effectiveness of counterpoise assistance with the ARM Guide because the patient cannot stretch his arm through its full passive range of motion. Thus, the patient's arm does not receive optimal therapy for treating tone. A possible solution is to compensate for the internal friction forces in the arm and device that produced the hysteresis in Fig. 2, since these forces were as large as 10 N. The patient could then exert a smaller force to extend the arm, although a larger force would be required to flex the arm (unless a controller were implemented that varied the assisting force depending on the desired direction of movement). From a broader perspective, however, it is likely that some stroke patients cannot generate *any* force for reaching with the arm in some configurations, as extrapolation of the above measurements of the rapid decrement in force production implies. Thus, an alternate approach to the assistive control law design was considered.

4.2. Control law 2: triggered assistance

The concept behind the second control law was to allow the patient to initiate movement, but to use the motor to complete the movement through the full passive range of motion if the patient is unable. A similar approach has recently been advocated in [13].

To achieve triggered assistance with the ARM Guide, a proportional/derivative position feedback controller is activated when the subject reaches beyond the start position by a small window r_s (see Table 2). The controller then drives the arm along a smooth (i.e. minimum-jerk) desired position trajectory, with the initial position of the desired trajectory matched to the start condition when the subject leaves the initial window and the final position set at the subject's full passive range of motion. A position dead-band of width δ is placed around the desired trajectory, such that if the subject follows the desired trajectory within this dead-band, the motor does not apply force (*cf.* [5, 8]). Also, the gains of the position feedback controller are exponentially increased from zero to a final stiff, damped value with a time constant τ. Exponentially increasing the gains was found to guide the arm smoothly toward the desired trajectory at the beginning of movement, while ensuring that the desired range of arm movement is completed if the subject is unable.

4.2.1. Evaluation of triggered assistance. The triggered assistance controller was tested with two severely impaired chronic stroke subjects (aged 38 and 31; 6 and 2 years post-stroke, respectively). An example of an assisted reach is given in Fig. 5.

Table 2.
Governing equations for triggered assistance with the ARM Guide. r = reach distance along linear bearing of ARM guide; r_s = size of initial trigger window; r_d = desired reach; δ = width of position deadband; K, B = controller gains; F = force applied by motor

Proportional–derivative servo, triggered at movement onset	$F = \begin{matrix} 0 & r(t) < r_s \\ -Ke - B\dot{e} & r(t) \geqslant r_s \end{matrix}$
Minimum-jerk desired trajectory, matched to start conditions	$r_d = a_0 + a_1(t - t_0) + a_2(t - t_0)^2 + a_3(t - t_0)^3 + a_4(t - t_0)^4 + a_5(t - t_0)^5$ $t_0 \equiv t_s - t_d$ where $r_d(t_d) = r_s \quad r(t_s) = r_s$
Position deadband	$e = \begin{matrix} r - r_d - \delta & e > \delta \\ r - r_d + \delta & e < \delta \\ 0 & \text{else} \end{matrix}$
Exponentially increasing gains	$K = K_f(1 - e^{-(t-t_0)/\tau}) \quad t > t_0$ $B = B_f(1 - e^{-(t-t_0)/\tau})$
Parameter values for controller evaluation	$r_s = 0.5$ cm $\quad \delta = 1.0$ cm $\quad \tau = 1.0$ s

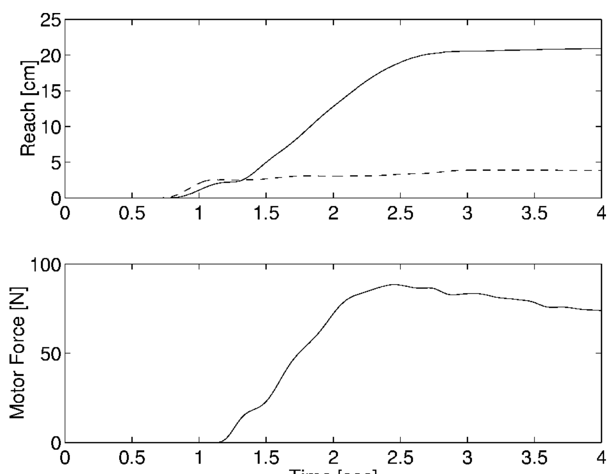

Figure 5. Example of triggered assistance. The patient initiates movement at time ≈0.7 s (solid line, top). The ARM Guide senses this movement, and applies an assistive force to gradually drive the arm smoothly through its full passive range of motion (bottom). An unassisted reach is shown for comparison (dashed line, top).

As can be seen, the motor began applying force after the subject initiated reaching and exceeded a small position threshold. The arm was then driven smoothly through its full passive range of motion along the desired minimum jerk trajectory.

Triggered assistance was further tested with the ARM Guide in five pitch and yaw combinations [(yaw,elevation) $=$ $\{(0.0^\circ, 0.0^\circ), (-22.5^\circ, 0.0^\circ), (+22.5^\circ, 0.0^\circ), (-22.5^\circ, 30.0^\circ), (+22.5^\circ, 30.0^\circ)\}$]. An unexpected finding was that the two subjects could not always reliably initiate reaching, and that their ability to initiate reaching depended on the orientation of the ARM Guide. The subjects had particular difficulty in initiating movement with the ARM Guide in an externally rotated position, being able to initate only 27 and 0%, respectively, of 20 reaches attempted with the device externally rotated (yaw $= +22.5^\circ$), as compared to 80 and 75% with the device internally rotated (yaw $= -22.5^\circ$). This difficulty again indicated an agonist weakness that depended strongly on arm configuration, specifically, on the subject's shoulder internal/external rotation angle. However, when subjects could initiate movement successfully, the triggered assistance did drive their arm through its full passive range of motion, thus providing the desired stretching for treating tone, as well as allowing the subjects to practice initiating and controlling movement.

5. DISCUSSION AND CONCLUSION

The primary unique features of the mechanical design of the ARM Guide are the use of a single motor and a linear constraint, along with two passive, compliant d.o.f. for orienting the device. The resulting design allows assisted reaching across the patient's workspace, while providing a simple means to inform subjects of incoordination during assisted reaching. Use of a single actuated d.o.f. and two passive compliant d.o.f. reduces the cost and improves the safety of the device as compared to robotic therapy devices with multiple active d.o.f. [9, 11]. However, in comparison, the ARM Guide is more limited in the patterns of forces it can apply to the arm.

The two controller designs for active assist therapy were found to be susceptible to configuration-dependent weakness, i.e. for certain configurations of the arm (elbow extended, shoulder externally rotated), the subjects had difficulty generating force for reaching. In the case of counterpoise assistance, this configuration-dependent weakness limited range of motion and thus effective stretching of soft tissues. In the case of triggered assistance, a full stretch of the arm was achieved, but configuration-dependent weakness limited self-initiation of movement when the shoulder was externally rotated. These results underscore the need to fully understand the nature of the movement impairment after stroke in order to optimize controller design.

As a specific example of the implication of these results to other devices, consider the potential application of 'extenders' [22] as assistive devices for stroke patients. Extenders are devices that amplify the strength of the user. However, because of configuration-dependent weakness, stroke patients may not have sufficient residual strength to allow suitable amplification in all arm configurations. Modifications to current extender control law designs, taking into account configuration-dependent weakness, may be possible.

We have recently begun using the ARM Guide to deliver active assist therapy to patients using the triggered assistance controller. To overcome configuration-dependent weakness, a program option was added so that the experimenter can manually trigger a movement for the patient when necessary. Preliminary results with two severely impaired, chronic stroke subjects are encouraging [23]. Both subjects significantly improved their active range of motion and peak velocity of movement along the ARM Guide with training, while also reducing tone. In addition, subjects learned to overcome configuration dependent weakness through repetitive attempts at initiating movement. Taken together with the positive preliminary results generated by other rehabilitators for the arm after stroke [24, 25], these results are encouraging. Active assist therapy can improve motor recovery following stroke. Optimizing its effects through rational mechanical and controller design is a key challenge for future research.

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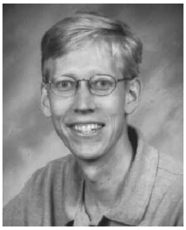
ABOUT THE AUTHORS



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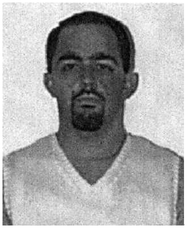

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