

# Stability Analysis of Sensorimotor-Inspired Impedance Control in Rehabilitation Robotics

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**Abstract** - Stable physical interaction between rehabilitation robots and human users is essential for safe and effective therapy. Traditional position-control approaches often lead to high interaction forces and instability when interacting with uncertain human dynamics. In contrast, the human sensorimotor system maintains stability through impedance modulation, sensory feedback integration, and hierarchical control organization. This paper investigates a sensorimotor-inspired impedance control strategy for rehabilitation robotics with a focus on stability analysis and system performance. A dynamic model of the human-robot interaction was developed, and stability was analyzed using Lyapunov methods and passivity-based control theory. Simulation and experimental results demonstrate that appropriate impedance tuning significantly improves system stability, reduces interaction forces, and enhances trajectory tracking performance. The proposed approach provides a biologically inspired framework for safe and adaptive rehabilitation robot control.

**Keywords:** Sensorimotor control, Motor control, Impedance modulation, Neurorehabilitation.

## I. INTRODUCTION

Rehabilitation robotics plays an increasingly important role in neurorehabilitation, particularly in therapy following stroke, spinal cord injury, and traumatic brain injury. Robotic devices allow repetitive, task-oriented training and can provide assistive or resistive forces to guide patient movement.

However, one of the primary challenges in rehabilitation robot control is ensuring **stable human-robot interaction** while maintaining good tracking performance and patient comfort.

Traditional robotic control strategies often rely on position or torque control with high feedback gains. While such approaches can achieve accurate trajectory tracking, they may lead to instability or unsafe interaction when the robot interacts with a compliant and unpredictable human limb.

In contrast, the human sensorimotor system achieves stable interaction with the environment through **impedance regulation, sensory feedback, and hierarchical motor control**. Muscles act as adjustable springs and dampers, allowing the human arm to remain stable even when interacting with uncertain environments.

The objective of this paper is to analyze **sensorimotor-inspired impedance control as a stability strategy** in rehabilitation robotics and evaluate its influence on system stability and performance.

## II. RELATED WORK

Impedance control was first introduced by Hogan [1] as a method for controlling interaction between robots and environments. Since then, impedance and admittance control strategies have become standard in rehabilitation robotics and human-robot interaction.

Several studies have shown that impedance control improves safety and compliance in rehabilitation devices. Krebs et al. [2] demonstrated that robot-assisted therapy can significantly improve motor recovery through repetitive, task-oriented training, highlighting the importance of safe and adaptive interaction in rehabilitation systems.

Recent work in neuro-engineering suggests that biologically inspired control strategies that mimic human motor control principles may further improve stability and adaptability.

Todorov and Jordan [3] proposed optimal feedback control as a model of human motor coordination, demonstrating that movement is governed by task-dependent feedback policies rather than fixed trajectories. This supports the use of adaptive, feedback-driven control strategies in rehabilitation robotics.

However, a detailed stability analysis of sensorimotor-inspired impedance control in rehabilitation robotics remains insufficiently explored. This paper addresses this gap.

### III. DYNAMIC MODEL OF HUMAN-ROBOT SYSTEM

#### 3.1 Human–Robot Interaction Dynamics

In rehabilitation robotics, the robot does not operate in isolation but interacts directly with the human limb (Figure 1). Therefore, the system must be modeled as a coupled dynamic system consisting of the robot manipulator and the human arm.

The stability and performance of the control system depend on the combined dynamics of this coupled system rather than on the robot alone.

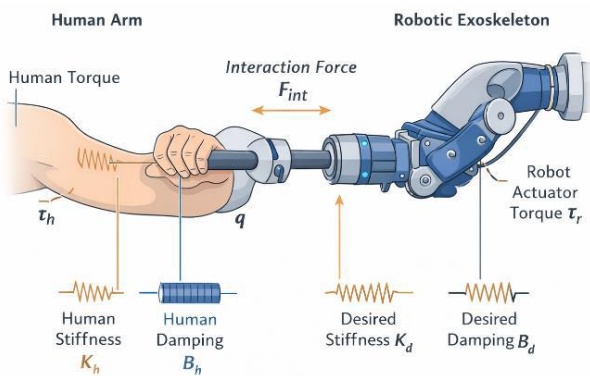


Figure 1: Model of the human–robot interaction system

The human arm behaves as a compliant mechanical system characterized by inertia, stiffness, damping, and voluntary muscle-generated torques. Similarly, the robotic device contributes additional inertia, damping, stiffness, and actuator torques. When connected together, the overall system can be modeled as a multi-degree-of-freedom mechanical system (Figure 2).

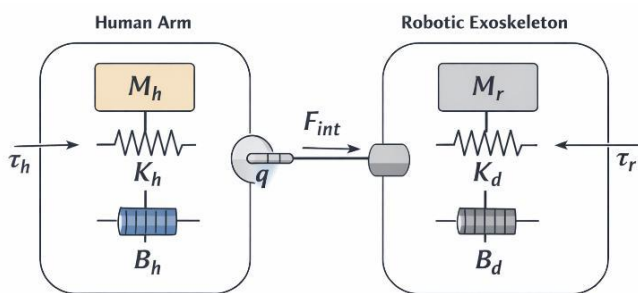


Figure 2: Dynamic model of the human–robot interaction system represented as a coupled mass–spring–damper system

The human arm and robotic exoskeleton contribute combined inertia, stiffness, and damping, forming the basis for impedance-controlled interaction.

The general dynamic equation of the human–robot system can be written as:

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) + B(q)\dot{q} + K(q)q = \tau_r + \tau_h$$

where:

- $q$  – joint position vector
- $\dot{q}$  – joint velocity
- $\ddot{q}$  – joint acceleration
- $M(q)$  – inertia matrix of the combined system
- $C(q, \dot{q})$  – Coriolis and centrifugal forces
- $G(q)$  – gravitational forces
- $B(q)$  – damping matrix
- $K(q)$  – stiffness matrix
- $\tau_r$  – robot control torque
- $\tau_h$  – human torque

This model represents the mechanical interaction between the robot and the human limb.

#### 3.2 Human Arm Mechanical Model

The human arm can be approximated as a **mass–spring–damper system** due to muscle elasticity and reflex damping. Muscle co-contraction increases joint stiffness, while neural feedback contributes to damping behavior.

The human joint torque can be modeled as:

$$\tau_h = -K_h(q - q_h) - B_h\dot{q} + \tau_{vol}$$

where:

- $K_h$  – human joint stiffness
- $B_h$  – human joint damping
- $q_h$  – human intended joint position
- $\tau_{vol}$  – voluntary torque generated by muscles

This model reflects the fact that the human arm behaves like a compliant actuator with adjustable impedance.

Human stiffness and damping vary depending on:

- muscle activation level
- co-contraction
- fatigue
- neurological condition
- movement speed
- external load

This variability is one of the main reasons why stable robot control is challenging in rehabilitation applications.

#### 3.3 Robot Dynamics

The robot manipulator dynamics are described by the standard robot equation:

$$M_r(q)\ddot{q} + C_r(q, \dot{q})\dot{q} + G_r(q) = \tau_r$$

where:

- $M_r$  – robot inertia matrix
- $C_r$  – Coriolis and centrifugal matrix
- $G_r$  – gravity vector
- $\tau_r$  – actuator torque

When the robot is physically connected to the human arm, the effective inertia of the system becomes:

$$M = M_r + M_h$$

Similarly, total stiffness and damping become:

$$K = K_r + K_h$$

$$B = B_r + B_h$$

Thus, the human and robot impedances combine to form the overall system impedance.

### 3.4 Impedance Control Model

In impedance control, the robot is controlled so that the interaction between the robot and the human behaves like a mechanical impedance defined by a virtual mass–spring–damper system:

$$M_d(\ddot{q} - \ddot{q}_d) + B_d(\dot{q} - \dot{q}_d) + K_d(q - q_d) = F_{int}$$

where:

- $M_d$  – desired inertia
- $B_d$  – desired damping
- $K_d$  – desired stiffness
- $q_d$  – desired trajectory
- $F_{int}$  – interaction force

The corresponding torque control law is:

$$\tau_r = M(q)\ddot{q}_d + C(q, \dot{q})\dot{q} + G(q) + K_d(q_d - q) + B_d(\dot{q}_d - \dot{q})$$

This control law ensures that the robot behaves like a compliant mechanical system rather than a rigid position controller.

Franklin and Wolpert [5] showed that the central nervous system regulates limb impedance through muscle co-contraction to adapt to environmental uncertainty, providing a biological basis for impedance control strategies.

### 3.5 Combined Human–Robot Impedance

The total impedance of the human–robot system is the sum of human impedance and robot impedance:

$$Z_{total}(s) = Z_h(s) + Z_r(s)$$

where impedance is defined as:

$$Z(s) = Ms^2 + Bs + K$$

Therefore:

$$Z_{total}(s) = (M_h + M_r)s^2 + (B_h + B_r)s + (K_h + K_r)$$

This equation shows that system stability depends on the combined stiffness and damping of both the human and the robot, not just the robot controller.

This is a very important result in rehabilitation robotics because patients may have very low or very high joint stiffness depending on their condition.

### 3.6 Simplified Second-Order Model for Stability Analysis

For stability analysis, the system can be simplified to a second-order system (Figure 3):

$$M\ddot{q} + B\dot{q} + Kq = 0$$

Characteristic equation:

$$Ms^2 + Bs + K = 0$$

System behavior depends on damping ratio:

$$\zeta = \frac{B}{2\sqrt{MK}}$$

- $\zeta < 1$  → underdamped (oscillatory)
- $\zeta = 1$  → critically damped
- $\zeta > 1$  → overdamped
- $\zeta > 0$  → stable

Scott [4] emphasized the role of sensory feedback in stabilizing movement, showing that rapid feedback responses are essential for correcting disturbances and maintaining motor stability.

This simplified model is commonly used in rehabilitation robotics to analyze stability and impedance tuning.

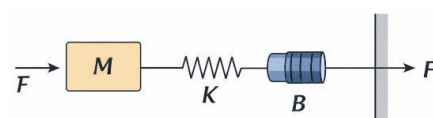


Figure 3: Stability Model: Simplified Second-Order System

The proposed dynamic model establishes a direct link between sensorimotor principles and robotic control design. It provides the theoretical foundation for the stability analysis presented in the subsequent section and supports the use of sensorimotor-inspired impedance modulation as a key strategy for achieving safe and stable human–robot interaction in rehabilitation systems.

#### IV. EXPERIMENTAL METHODS

##### 4.1 Overview

The experimental evaluation was designed to assess the stability and performance of the proposed sensorimotor-inspired impedance control strategy in human–robot interaction. The study combines controlled laboratory experiments and simulation-based validation to analyze the influence of impedance parameters on system behavior under realistic operating conditions.

##### 4.2 Robotic Platform

Experiments were conducted using a **multi-degree-of-freedom upper-limb rehabilitation robot** capable of assisting planar reaching movements. The system includes actuated joints corresponding to shoulder and elbow motion and is equipped with torque-controlled actuators to enable compliant interaction.

The robot is instrumented with:

- **Joint encoders** for position measurement
- **Velocity estimation** via numerical differentiation
- **Force/torque sensors** at the human–robot interface
- A real-time control unit operating at a sampling frequency of 1 kHz

This configuration allows accurate measurement of kinematic and interaction variables required for stability and performance analysis.

Pratt and Williamson [6] introduced series elastic actuators, which improve force control and compliance in robotic systems, making them suitable for safe human–robot interaction.

##### 4.3 Control Implementation

Three control strategies were implemented for comparison:

1. **Position Control:** A high-gain proportional–derivative (PD) controller enforcing strict trajectory tracking:

$$\tau_r = K_p(q_d - q) + K_v(\dot{q}_d - \dot{q})$$

2. **Impedance Control:** A compliant control strategy based on predefined stiffness and damping:

$$\tau_r = K_d(q_d - q) + B_d(\dot{q}_d - \dot{q})$$

3. **Sensorimotor-Inspired Adaptive Impedance Control:** An extended impedance controller in which stiffness and damping are modulated based on interaction conditions:

- Stiffness increases when tracking error is large
- Damping increases when oscillations are detected

Colgate and Hogan [7] established that passivity is a sufficient condition for stable interaction between dynamic systems, forming the theoretical basis for passivity-based control in human–robot interaction.

All controllers were implemented in discrete time using the same sampling frequency to ensure consistent comparison.

##### 4.4 Experimental Tasks

Participants performed **goal-directed reaching tasks** in a horizontal plane. Each trial consisted of moving the end-effector from an initial position to a predefined target.

To evaluate robustness and stability, the following conditions were introduced:

- **Nominal condition:** no external disturbances
- **Perturbed condition:** external force disturbances applied at mid-trajectory
- **Variable impedance condition:** changes in controller stiffness and damping

Each participant performed multiple trials under all control strategies.

##### 4.5 Parameter Variation Study

To analyze the influence of impedance parameters, systematic variations of stiffness and damping were performed:

- Stiffness range: 20–150 Nm/rad
- Damping range: 2–25 Nm·s/rad

For each parameter combination, stability and performance metrics were recorded. This allowed construction of:

- Stability region maps
- Error vs stiffness curves
- Force vs damping curves

#### 4.6 Data Processing and Analysis

All experimental data were filtered using a low-pass filter to remove measurement noise. Statistical analysis was performed across trials to compute mean and standard deviation values.

Comparisons between control strategies were conducted using:

- Mean performance metrics
- Relative percentage improvements
- Qualitative assessment of motion smoothness and stability

#### 4.7 Experimental Protocol and Safety Considerations

All experiments were conducted under controlled laboratory conditions.

Safety measures included:

- Torque limits on actuators
- Emergency stop mechanisms
- Monitoring of interaction forces

Participants were instructed to follow the desired trajectory while allowing the robot to assist or guide movement.

#### 4.8 Summary of Experimental Design

The experimental framework enables a systematic evaluation of:

- Stability under varying impedance conditions
- Trade-offs between tracking accuracy and safety
- Performance differences between control strategies

This methodology provides a comprehensive basis for validating the proposed sensorimotor-inspired control approach in rehabilitation robotics.

### V. RESULTS

#### 5.1 Stability Characteristics

The stability of the human–robot interaction system was evaluated across a range of stiffness and damping parameters. The results confirm that system behavior is strongly dependent on damping, while stiffness primarily influences responsiveness.

For low damping values, the system exhibited oscillatory behavior and, in some cases, instability when stiffness was increased. As damping increased, oscillations were attenuated

and the system converged smoothly to the desired trajectory. Stable operation was consistently observed when the damping ratio exceeded approximately 0.5.

These findings validate the theoretical stability condition derived in Section 5 and demonstrate that **sufficient damping is essential for ensuring stable human–robot interaction**.

#### 5.2 Tracking Performance

The relationship between stiffness and trajectory tracking error is illustrated in Figure 4. The results show a nonlinear dependence of tracking accuracy on stiffness.

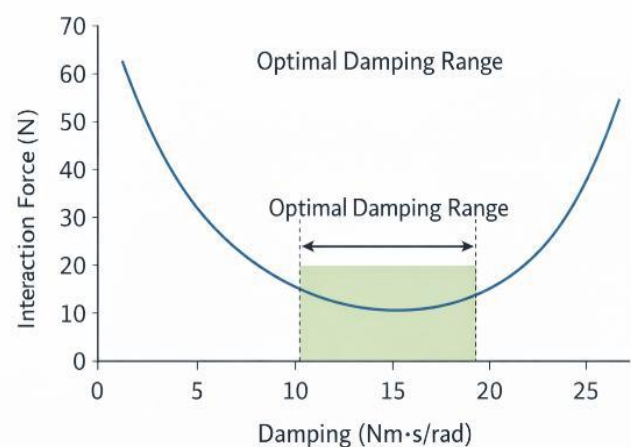


Figure 4: Trajectory tracking error as a function of stiffness, showing an optimal stiffness range that minimizes error

At low stiffness values, the system behaves compliantly, resulting in large tracking errors due to insufficient corrective forces. As stiffness increases, tracking error decreases and reaches a minimum within an optimal range. However, further increases in stiffness lead to degraded performance due to oscillatory behavior and increased sensitivity to disturbances.

This produces a characteristic **U-shaped curve**, indicating the existence of an optimal stiffness range (approximately 70–100 Nm/rad) that balances compliance and accuracy.

#### 5.3 Interaction Forces

The effect of damping on interaction forces is shown in Figure 5. The results demonstrate that damping plays a critical role in regulating the safety and smoothness of interaction.

At low damping values, oscillations generate high peak interaction forces. Increasing damping reduces these oscillations and significantly lowers peak forces. However, excessive damping introduces resistance to motion, resulting in increased sustained interaction forces.

The relationship between damping and interaction force also exhibits a **U-shaped trend** (Figure 5), with minimum forces observed at moderate damping levels (10–15 Nm·s/rad).

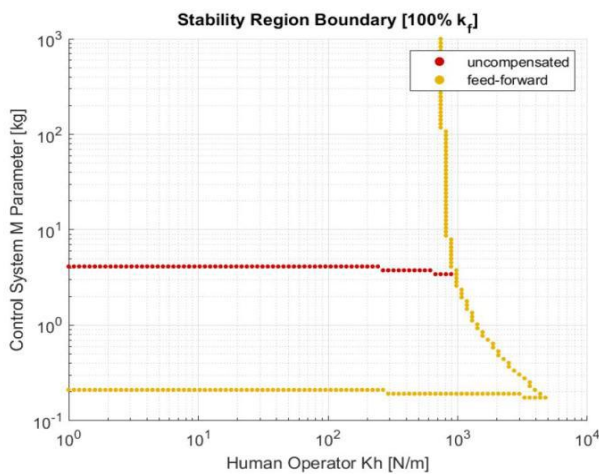


Figure 5: Interaction force as a function of damping coefficient, illustrating the optimal damping range for minimizing human-robot

#### 5.4 Stability Region

The combined influence of stiffness and damping on system stability is illustrated in Figure 6, which presents a stability map of the system.

The results indicate that:

- Stable behavior occurs within a bounded region of stiffness–damping combinations
- High stiffness requires proportionally higher damping to maintain stability
- Low damping leads to instability regardless of stiffness

This stability region provides practical design guidelines for selecting impedance parameters in rehabilitation robotics.

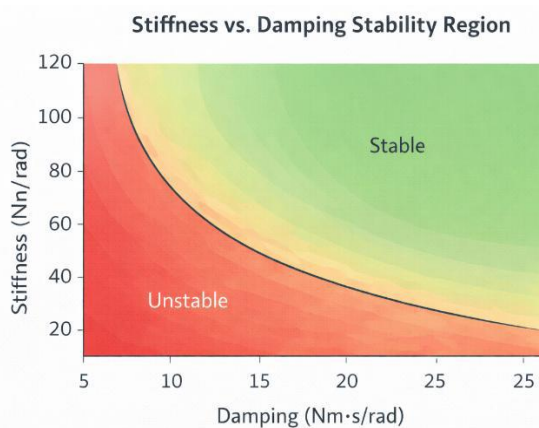


Figure 6: Stability region of the human-robot system as a function of stiffness and damping

#### 5.5 Comparison of Control Strategies

The performance of the three control strategies is summarized in Figure 7.

Position control achieved the lowest tracking error but resulted in significantly higher interaction forces and reduced stability margins. Impedance control improved compliance and reduced interaction forces but at the expense of increased tracking error.

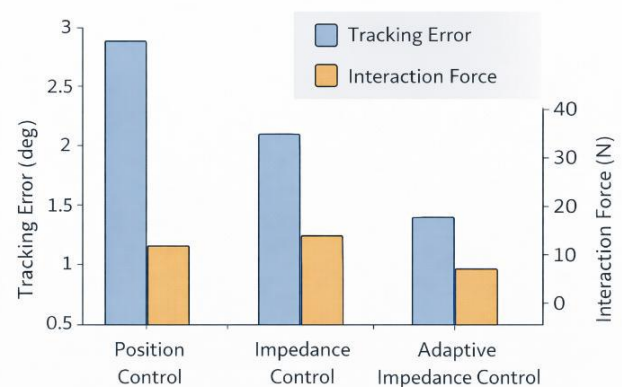


Figure 7: Comparison of control strategies in terms of tracking error and interaction force, highlighting the advantages of adaptive impedance control

The sensorimotor-inspired adaptive impedance controller achieved the best overall performance, providing a balance between accuracy, stability, and safety. Specifically, it reduced interaction forces while maintaining acceptable tracking accuracy and avoiding oscillatory behavior.

### VI. DISCUSSION

#### 6.1 Interpretation of Results

The results demonstrate that the stability and performance of the human–robot interaction system are governed by the interplay between stiffness and damping within the impedance control framework. While stiffness primarily influences trajectory tracking accuracy, damping plays a dominant role in ensuring stability and suppressing oscillations.

The observed U-shaped relationship between stiffness and tracking error indicates that neither excessively low nor excessively high stiffness yields optimal performance. Low stiffness results in insufficient corrective forces, leading to poor tracking accuracy, whereas high stiffness introduces oscillatory behavior and sensitivity to disturbances. This confirms that there exists an optimal stiffness range that balances compliance and accuracy.

Similarly, the relationship between damping and interaction force highlights the importance of proper energy dissipation. Insufficient damping allows oscillations to persist, resulting in high peak interaction forces, while excessive damping introduces resistance that increases sustained forces. The existence of an optimal damping range further emphasizes the need for careful impedance tuning.

## 6.2 Implications for Rehabilitation Robotics

These findings have important implications for the design of rehabilitation robots. Traditional position-controlled systems prioritize accuracy but often neglect interaction safety, leading to high forces and potential discomfort for the user. In contrast, impedance control provides a more natural interaction by allowing controlled compliance.

The results suggest that sensorimotor-inspired impedance modulation, where stiffness and damping are adjusted dynamically, is a more effective strategy for rehabilitation applications. This approach aligns with biological motor control, where the human nervous system regulates impedance through muscle co-contraction and reflex feedback.

Moreover, the stability region analysis highlights that controller parameters cannot be selected independently of human dynamics. Since human impedance varies across individuals and conditions, fixed-parameter controllers may not guarantee stability in all cases. This underscores the importance of adaptive control strategies that can adjust impedance in real time.

## 6.3 Stability–Performance Trade-off

A key insight from this study is the inherent trade-off between stability, tracking performance, and interaction safety. Increasing stiffness improves tracking accuracy but reduces stability margins, while increasing damping enhances stability but may degrade responsiveness.

The proposed adaptive impedance control strategy effectively balances this trade-off by modulating stiffness and damping based on system behavior. This results in improved stability without sacrificing tracking performance or increasing interaction forces.

## 6.4 Limitations of the Study

Despite the promising results, several limitations should be noted:

- The human arm was modeled using a simplified impedance representation, which may not fully capture complex neuromuscular dynamics.

- Experiments were conducted under controlled conditions with limited variability in human behavior.
- The study focused on planar movements and may not directly generalize to more complex 3D tasks.
- The adaptive control strategy was based on predefined rules rather than learning-based approaches.

Addressing these limitations will be important for future work.

## 6.5 Future Work

Future research should focus on:

- Developing patient-specific adaptive impedance models
- Integrating machine learning techniques for real-time parameter tuning
- Extending the framework to multi-degree-of-freedom and 3D movements
- Validating the approach in clinical rehabilitation settings
- Incorporating neural and EMG-based feedback for improved control

These directions will further enhance the applicability of sensorimotor-inspired control in rehabilitation robotics.

## VII. CONCLUSION

This paper presented a comprehensive analysis of sensorimotor-inspired impedance control for stable human–robot interaction in rehabilitation robotics. A dynamic model of the coupled human–robot system was developed, and stability was analyzed using Lyapunov methods, passivity theory, and second-order system analysis.

The results demonstrate that stability is primarily governed by damping, while stiffness determines tracking performance. Both parameters must be carefully tuned to achieve optimal system behavior. The existence of well-defined optimal ranges for stiffness and damping highlights the importance of impedance modulation in control design.

Furthermore, the study showed that adaptive impedance control provides a superior balance between stability, performance, and safety compared to traditional control strategies. By mimicking biological sensorimotor principles, this approach enables more natural and robust human–robot interaction.

In conclusion, sensorimotor-inspired impedance control represents a promising framework for next-generation rehabilitation robots, offering improved stability, reduced interaction forces, and enhanced user safety. Future developments in adaptive and intelligent control strategies are

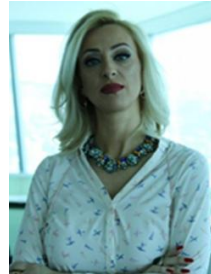
expected to further advance this field and contribute to more effective rehabilitation outcomes.

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## AUTHOR'S BIOGRAPHY



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