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Translational Modelling of the Human Sensorimotor System for Biomechanical and Prosthetic Applications

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Abstract **- Translational modelling aims to bridge biological motor control principles and engineering implementations in robotics, prosthetics, and rehabilitation systems. This paper presents a translational modelling framework based on a dynamic model of the human upper extremity and hierarchical sensorimotor control architecture. The model integrates rigid-body dynamics, inverse dynamics control, optimal trajectory planning, and sensory feedback adaptation. The objective is not only to simulate human movement but to translate biological control principles into engineering control architectures applicable to robotic manipulators and prosthetic devices. Simulation results demonstrate that hierarchical control and redundancy-based flexibility can be successfully implemented in engineering systems, improving robustness and adaptability to perturbations. The study shows that translational modelling provides a systematic pathway from neuroscience and biomechanics to robotics and prosthetic control system design.**

Keywords: translational modelling, sensorimotor system, prosthetics, robotics, biomechanical modelling, hierarchical control.

I. INTRODUCTION

Understanding human motor control has long been a central problem in biomechanics, neuroscience, robotics, and rehabilitation engineering. The human sensorimotor system demonstrates adaptability, robustness, and efficiency that engineering systems still struggle to replicate. Translational modelling represents an interdisciplinary approach in which biological principles are translated into mathematical models and engineering control systems.

Traditional biomechanical models often focus only on movement simulation, while robotic control systems are frequently developed independently from biological motor control principles. Translational modelling aims to bridge this gap by creating models that simultaneously describe biological movement and provide a framework for engineering system design.

The human upper extremity is particularly suitable for translational modelling due to its redundancy, hierarchical control organization, and adaptability. By modelling the dynamics and control of the upper extremity, we can derive principles applicable to robotic manipulators, rehabilitation robots, and active prosthetic devices.

This paper presents a translational modelling framework based on:

- dynamic modelling of the upper extremity,
- hierarchical sensorimotor control,
- inverse dynamics control,
- feedback adaptation,
- redundancy and motor equivalence.

The goal is to demonstrate how biological motor control principles can be translated into engineering control architectures.

The control of human movement is characterized by redundancy and flexibility of the musculoskeletal system, commonly referred to as the degrees-of-freedom problem first described by Bernstein [1].

Human reaching movements are often described by minimum-jerk trajectories, which minimize the third derivative of position and produce smooth motion [9].

Optimal feedback control theory suggests that the nervous system minimizes movement variability and effort while achieving task goals [2,3].

Biomechanical modelling and simulation are widely used to study human movement and motor control strategies [5,12].

Translational modelling connects biomechanical models and engineering control systems for robotic and prosthetic applications [18,19].

II. TRANSLATIONAL MODELLING FRAMEWORK

Translational modelling represents an interdisciplinary methodology that connects biological motor control, biomechanical modelling, control theory, robotics, and prosthetic engineering into a unified modelling and control framework. The primary objective of translational modelling is not only to simulate biological movement but to translate principles of human sensorimotor control into engineering systems such as robotic manipulators, exoskeletons, and active prosthetic limbs.

Unlike traditional biomechanical modelling, which often focuses on movement analysis, translational modelling focuses on **mapping biological control structures into engineering control architectures**. This approach allows insights from neuroscience and biomechanics to directly influence the design of artificial movement systems.

2.1 Concept of Translational Modelling

The human sensorimotor system can be viewed as a control system consisting of:

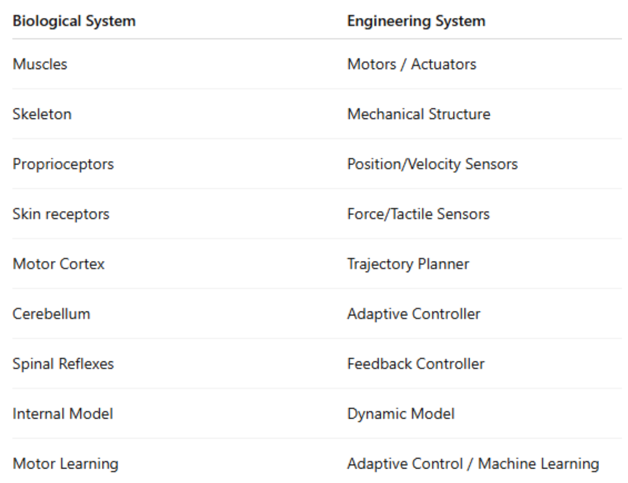
- a mechanical system (musculoskeletal system),
- actuators (muscles),
- sensors (proprioception, vision, tactile sensing),
- controllers (central nervous system),
- internal models,
- learning and adaptation mechanisms.

Similarly, engineering systems such as robotic arms or prosthetic limbs consist of:

- mechanical structure,
- actuators (electric motors, hydraulic actuators),
- sensors (encoders, force sensors, IMUs),
- controllers,
- dynamic models,
- adaptive algorithms.

Translational modelling establishes a **functional mapping between these two systems**, allowing biological motor control principles to be implemented in engineering devices.

This mapping can be expressed conceptually as:



Biological System	Engineering System
Muscles	Motors / Actuators
Skeleton	Mechanical Structure
Proprioceptors	Position/Velocity Sensors
Skin receptors	Force/Tactile Sensors
Motor Cortex	Trajectory Planner
Cerebellum	Adaptive Controller
Spinal Reflexes	Feedback Controller
Internal Model	Dynamic Model
Motor Learning	Adaptive Control / Machine Learning

This mapping is fundamental to translational modelling and allows engineering systems to mimic biological movement behaviour.

2.2 Levels of Translational Modelling

Translational modelling can be divided into several hierarchical levels, each representing a transformation from biological observation to engineering implementation.

Level 1 – Biological Observation

At the first level, experimental observations are made regarding human movement, muscle activation patterns, joint coordination, motor learning, and adaptation. This includes studies from biomechanics, neuroscience, and motor control research. Typical observations include:

- smooth trajectories in reaching movements,
- redundancy and motor equivalence,
- impedance modulation,
- reflex-based feedback corrections,
- learning and adaptation,
- hierarchical organization of control.

These biological principles serve as the foundation for translational modelling.

Level 2 – Biomechanical Modelling

The second level involves constructing biomechanical models of the human body or body segments. These models include:

- rigid body dynamics,
- joint kinematics,
- muscle models,
- force generation models,
- contact and interaction models.

The biomechanical model provides a mathematical representation of the human movement system and allows simulation and analysis of movement dynamics.

Level 3 – Mathematical and Dynamic Modelling

At this level, biomechanical models are translated into mathematical equations describing system dynamics. Typically, these equations are derived using:

- Euler–Lagrange formulation,
- Newton–Euler formulation,
- multibody dynamics,
- state-space modelling.

The general dynamic equation for both human limbs and robotic manipulators is:

$$\tau = M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q)$$

This equation is extremely important in translational modelling because it is **identical for biological limb dynamics and robotic manipulator dynamics**, making it a direct bridge between biomechanics and robotics.

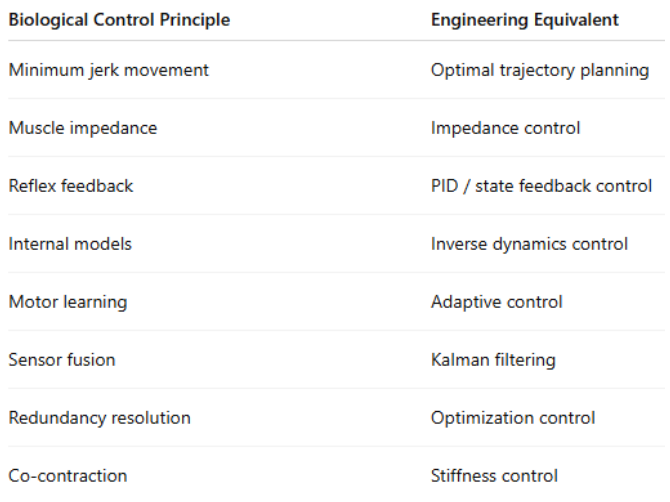
Thus, the same mathematical model can be used for:

- human movement simulation,
- robot control,
- prosthetic limb control,
- exoskeleton control.

This represents one of the key principles of translational modelling.

Level 4 – Control System Translation

The next level involves translating biological control strategies into engineering control algorithms. The human sensorimotor system uses several control principles that can be translated into engineering control methods:



Biological Control Principle	Engineering Equivalent
Minimum jerk movement	Optimal trajectory planning
Muscle impedance	Impedance control
Reflex feedback	PID / state feedback control
Internal models	Inverse dynamics control
Motor learning	Adaptive control
Sensor fusion	Kalman filtering
Redundancy resolution	Optimization control
Co-contraction	Stiffness control

This level is crucial because it transforms biological movement principles into implementable control algorithms.

Level 5 – Engineering Implementation

At this level, the translational model is implemented in engineering systems such as:

- robotic manipulators,
- rehabilitation robots,
- powered prosthetic limbs,
- exoskeletons,
- humanoid robots,
- human–robot interaction systems.

The translational modelling process ensures that these systems behave more like biological systems rather than purely mechanical systems.

2.3 Translational Modelling as a Closed-Loop System

One of the most important aspects of translational modelling is that it should not be viewed as a one-way process from biology to engineering. Instead, it is a **closed-loop research process**:

1. Biological observation
2. Biomechanical modelling
3. Mathematical modelling
4. Control system design
5. Engineering implementation
6. Experimental testing
7. Comparison with human movement
8. Model refinement

Thus, engineering systems can also be used to test hypotheses about human motor control, meaning that translational modelling works in both directions:

- Biology → Engineering
- Engineering → Biology

This approach is often used in neuroprosthetics, rehabilitation robotics, and motor control research.

2.4 Translational Modelling and Redundancy

A major characteristic of the human motor system is redundancy, meaning that there are more degrees of freedom than necessary to perform a task. Translational modelling must therefore include redundancy resolution methods.

In biological systems, redundancy allows:

- flexibility,
- obstacle avoidance,
- compensation for injury,
- energy optimization,
- variability without loss of task performance.

In engineering systems, redundancy can be implemented using optimization methods such as:

- minimum torque,
- minimum energy,
- minimum jerk,
- minimum torque change,

- optimal feedback control,
- quadratic programming,
- null-space control.

Thus, translational modelling does not eliminate redundancy but instead **translates biological redundancy into optimization-based control strategies.**

2.5 Translational Modelling for Prosthetic Systems

One of the most important applications of translational modelling is prosthetic limb control. Traditional prosthetic devices often use simple position or velocity control, which does not produce natural movement. Translational modelling allows prosthetic limbs to use control strategies similar to biological limbs.

Translational prosthetic control may include:

- inverse dynamics control,
- impedance control,
- EMG-based control,
- adaptive control,
- sensor fusion,
- predictive control,
- hierarchical control architecture.

These results in prosthetic devices that:

- move more naturally,
- require less cognitive effort from the user,
- adapt to terrain and tasks,
- reduce energy consumption,
- improve comfort and usability.

2.6 Summary of Translational Modelling Framework

The translational modelling framework developed in this paper can be summarized as a multi-layer transformation process:

Biological System → Biomechanical Model → Mathematical Model → Control Architecture → Engineering System

This framework forms a bridge between:

- neuroscience,
- biomechanics,
- control theory,
- robotics,
- prosthetics,
- rehabilitation engineering.

Translational modelling therefore represents a unified approach for developing biomimetic robotic and prosthetic systems based on principles of human motor control rather than purely mechanical control strategies.

Biomechanical models of human movement are commonly based on rigid-body dynamics and multibody system modelling [5,12].

Similar dynamic formulations are used in robotic manipulator modelling and control [6,7].

Translational modelling aims to bridge biological motor control and engineering control systems by translating sensorimotor control principles into robotic and prosthetic control architectures [18,19].

Impedance control and optimal feedback control represent important concepts connecting biological and robotic control strategies [2,4].

III. HIERARCHICAL TRANSLATIONAL CONTROL ARCHITECTURE

The hierarchical organization of the human sensorimotor system is one of its most important characteristics and represents a fundamental principle for translational modelling. Human movement is not controlled at a single level but emerges from multiple interacting layers of planning, prediction, execution, and feedback correction. Translational modelling aims to replicate this hierarchical structure in engineering systems such as robotic manipulators, prosthetic limbs, and rehabilitation robots.

The hierarchical translational control architecture developed in this study is structured into multiple control layers that correspond to functional levels of biological motor control. These layers operate at different time scales and levels of abstraction, from high-level task planning to low-level torque control and reflex-like feedback responses.

3.1 Hierarchical Control in Biological Systems

In the human motor system, movement control is distributed across several levels of the nervous system. These levels include cortical planning areas, cerebellar prediction and adaptation mechanisms, brainstem coordination centers, and spinal reflex loops. Rather than acting independently, these levels form a hierarchical control structure in which higher levels define movement goals and lower levels execute and stabilize movement.

At the highest level, movement intention and task planning are generated. This includes decisions such as reaching for an object, grasping, or avoiding an obstacle. At intermediate levels, the nervous system transforms task goals into joint trajectories and muscle activation patterns. At the lowest level, reflex mechanisms and muscle dynamics ensure stability and rapid response to perturbations.

This hierarchical organization allows the motor system to achieve both flexibility and robustness. High-level planning allows adaptation to new tasks, while low-level feedback ensures stability and rapid correction of disturbances.

Translational modelling attempts to replicate this architecture in engineering control systems.

3.2 Structure of the Hierarchical Translational Control System

The hierarchical translational control architecture proposed in this work consists of five main layers:

1. Task-Level Planning Layer
2. Trajectory Generation Layer
3. Inverse Dynamics / Internal Model Layer
4. Feedback Control Layer
5. Adaptation and Learning Layer

Each layer performs a specific function and operates at a different time scale. Together, they form a closed-loop control system capable of generating adaptive and robust movement.

3.3 Task-Level Planning Layer

The task-level planning layer represents the highest level of the hierarchical control architecture. At this level, movement goals are defined in task space rather than joint space. Examples of task-level goals include moving the hand to a target position, following a trajectory, applying a specific force, or manipulating an object.

In translational modelling, this layer corresponds to high-level planning algorithms used in robotics and prosthetics. The output of this layer is typically a desired trajectory for the end-effector position, velocity, and acceleration.

Movement planning at this level is often based on optimization principles. One of the most widely used principles in biological movement modelling is the minimum-jerk principle, which states that human movements tend to minimize the rate of change of acceleration. This results in smooth and natural-looking trajectories.

Other optimization criteria that may be used include:

- minimum energy,
- minimum torque change,
- minimum effort,
- minimum variance,
- optimal feedback control.

The task-level planner therefore generates desired trajectories that are smooth, efficient, and biologically plausible. This trajectory is then passed to the next layer of the control hierarchy.

3.4 Trajectory Generation Layer

The trajectory generation layer transforms task-level goals into time-dependent trajectories in Cartesian or joint space. This layer determines how the movement will be executed over time, including velocity and acceleration profiles.

In biological systems, trajectory planning is believed to occur in motor cortical areas and involves internal models of limb dynamics and environmental interaction. In translational modelling, trajectory generation is implemented using polynomial trajectories, spline interpolation, or optimal control methods.

The trajectory generator outputs:

- desired position,
- desired velocity,
- desired acceleration.

These variables are necessary for inverse dynamics control, which calculates the required joint torques.

Trajectory smoothness is extremely important in both biological and engineering systems because discontinuities in acceleration or jerk result in large torque peaks and inefficient movement. Therefore, trajectory generation plays a critical role in energy efficiency and movement naturalness.

3.5 Inverse Dynamics and Internal Model Layer

The inverse dynamics layer is one of the most important components of the hierarchical translational control architecture. This layer transforms desired joint trajectories into required joint torques using the dynamic model of the system.

In biological motor control, this corresponds to internal models in the brain that predict the forces required to produce movement. These internal models allow the nervous system to generate feedforward motor commands before sensory feedback becomes available.

In translational modelling, the inverse dynamics controller computes torques using the dynamic equation of motion:

$$\tau = M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q)$$

This feedforward torque command allows accurate trajectory tracking and reduces the burden on the feedback controller. Without inverse dynamics control, the system would rely entirely on feedback, resulting in slower and less stable movement.

The inverse dynamics layer therefore acts as a predictive controller that compensates for system dynamics in advance.

3.6 Feedback Control Layer

The feedback control layer is responsible for correcting errors between desired and actual movement. This layer corresponds to sensory feedback mechanisms in biological systems, including proprioceptive feedback, visual feedback, and tactile feedback.

In engineering systems, feedback control can be implemented using:

- PID control,
- state feedback control,
- impedance control,
- admittance control,
- model predictive control,
- optimal feedback control.

The feedback controller receives sensor information such as joint position, velocity, and force, and generates corrective torques to reduce tracking error.

Feedback control is particularly important in the presence of:

- external disturbances,
- modelling errors,
- parameter uncertainty,
- interaction forces,
- environmental variability.

In hierarchical control architecture, feedback operates at a faster time scale than trajectory planning but slower than reflex-like low-level control loops.

3.7 Adaptation and Learning Layer

The highest level of sophistication in the hierarchical translational control architecture is the adaptation and learning layer. Biological motor control systems continuously adapt to changes such as muscle fatigue, injury, tool use, and environmental changes.

In translational modelling, adaptation can be implemented using:

- adaptive control,
- parameter estimation,
- neural networks,
- reinforcement learning,
- iterative learning control,
- Kalman filtering,
- disturbance observers.

The adaptation layer updates model parameters, control gains, or trajectory planning parameters to improve performance over time. This is particularly important in prosthetic systems, where device dynamics and user behaviour may change over time.

The adaptation layer allows the system to learn from repeated movements and improve accuracy, efficiency, and stability.

3.8 Interaction Between Hierarchical Layers

The hierarchical layers do not operate independently but interact continuously. The task planner defines movement goals, the trajectory generator produces desired motion profiles, the inverse dynamics controller generates feedforward torques, the feedback controller corrects errors, and the adaptation layer updates system parameters.

This multi-layer interaction allows the system to achieve:

- stability,
- robustness,
- adaptability,
- smooth movement,
- energy efficiency,
- redundancy resolution.

One of the key advantages of hierarchical control is that complex control problems are divided into smaller subproblems handled at different layers. This reduces computational complexity and improves system stability.

3.9 Translational Significance for Robotics and Prosthetics

The hierarchical translational control architecture is particularly suitable for robotic and prosthetic systems because it separates high-level task control from low-level actuator control. This allows prosthetic devices to interpret user intention at a high level while automatically handling low-level torque control and stabilization.

For example, in a prosthetic arm:

- The user intention defines the task goal.
- The trajectory planner generates movement trajectory.
- The inverse dynamics model calculates required torques.
- The feedback controller stabilizes movement.

- The adaptation layer adjusts control based on user behaviour.

This results in prosthetic devices that behave more like biological limbs rather than purely mechanical devices.

3.10 Summary of Hierarchical Translational Control Architecture

The hierarchical translational control architecture presented in this paper represents a biomimetic control framework inspired by the organization of the human sensorimotor system. The architecture consists of multiple layers responsible for planning, trajectory generation, dynamic compensation, feedback correction, and adaptation.

This hierarchical approach provides several advantages:

- improved stability,
- better disturbance rejection,
- smoother trajectories,
- reduced energy consumption,
- adaptability to changing conditions,
- natural movement behaviour,
- suitability for prosthetic and robotic applications.

The hierarchical translational control architecture therefore represents a key component in the development of biomimetic robotic systems and advanced prosthetic devices.

Human motor control is organized hierarchically with multiple control levels responsible for planning, execution, and feedback correction [3].

Internal models are believed to be used by the nervous system to predict required forces and compensate for system dynamics [11].

Optimal feedback control provides a theoretical framework for hierarchical motor control [2].

Operational space control and impedance control represent engineering implementations of similar hierarchical control concepts [4,14].

Hierarchical translational control architectures can be used in prosthetic and robotic systems to improve movement naturalness and adaptability [18,19].

IV. REDUNDANCY AND OPTIMIZATION IN TRANSLATIONAL MODELLING

Redundancy is one of the fundamental properties of the human sensorimotor system and plays a central role in translational modelling. The human musculoskeletal system contains more degrees of freedom than are strictly necessary to perform most motor tasks, which means that multiple joint configurations and muscle activation patterns can produce the same movement outcome. This characteristic provides flexibility, robustness, and adaptability, and must therefore be incorporated into translational models used for robotics and prosthetic systems.

In classical robotics, redundancy was often considered a problem that complicated control algorithms. However, in biological systems redundancy is clearly beneficial, allowing the motor system to adapt to perturbations, avoid obstacles, minimize energy consumption, and compensate for fatigue or injury. Translational modelling therefore does not attempt to eliminate redundancy but instead aims to **translate biological redundancy into optimization-based control strategies** that improve performance of engineering systems.

4.1 Redundancy in the Sensorimotor System and Mechanical Models

The redundancy of the human upper extremity arises from both kinematic and actuation redundancy. Kinematic redundancy occurs because the number of joint degrees of freedom exceeds the dimensionality of the task space. For example, positioning the hand in three-dimensional space requires only three coordinates, while the arm contains multiple joints that can achieve the same hand position using different joint configurations.

Actuation redundancy arises because multiple muscles can generate similar joint torques. This means that the nervous system must decide not only how to move the joints but also how to distribute forces among muscles.

Mathematically, redundancy can be described through the relationship between joint space and task space. The end-effector velocity is related to joint velocities through the Jacobian matrix:

$$\dot{x} = J(q)\dot{q}$$

If the system is redundant, the Jacobian matrix is not square and the inverse solution is not unique. The general solution for joint velocities is given by:

$$\dot{q} = J^{+}\dot{x} + (I - J^{+}J)z$$

The first term produces the desired end-effector motion, while the second term represents motion in the null space of the Jacobian, which does not affect end-effector movement. This null-space motion can be used to optimize secondary objectives such as minimizing energy consumption, avoiding joint limits, or maintaining stability.

This mathematical representation is very important in translational modelling because it allows redundancy observed in biological systems to be implemented in robotic manipulators and prosthetic limbs.

4.2 Optimization Principles in Translational Motor Control

Because redundant systems have infinitely many possible solutions, an optimization criterion must be used to select the most appropriate movement solution. Research in motor control suggests that the human nervous system optimizes certain performance criteria when generating movement.

Several optimization principles are commonly used in translational modelling:

- minimum energy,
- minimum torque change,
- minimum jerk,
- minimum joint stress,
- minimum movement variance,
- impedance optimization,
- optimal feedback control.

These optimization criteria can be implemented using cost functions that are minimized during trajectory planning or redundancy resolution. A common quadratic cost function used in robotics and biomechanical modelling is:

$$J = \tau^T W \tau$$

Where τ represents joint torques and W is a weighting matrix. Minimizing this cost function reduces actuator effort and energy consumption.

Another commonly used cost function is:

$$J = \dot{q}^T W \dot{q}$$

Which minimizes joint velocities and results in smooth movement trajectories.

Minimum jerk optimization is particularly important because experimental studies show that human reaching movements closely follow minimum jerk trajectories. Implementing minimum jerk trajectory planning in robotic and prosthetic systems results in movements that appear more natural and require less energy.

Optimization therefore represents the mechanism through which redundancy is resolved in translational modelling, allowing engineering systems to reproduce biological movement strategies.

4.3 Redundancy Resolution in Prosthetics and Robotic Systems

Redundancy resolution is particularly important in prosthetic limbs, exoskeletons, and robotic manipulators interacting with humans. In these systems, redundancy can be used to improve movement efficiency, safety, and adaptability.

In prosthetic systems, redundancy allows:

- adaptation to different walking or reaching strategies,
- compensation for actuator limitations,
- reduction of energy consumption,
- smoother and more natural movement,
- improved interaction with the environment,
- reduced mechanical stress on joints,
- user-specific movement adaptation.

For example, in an upper-limb prosthesis, multiple joint configurations may allow the user to reach the same object. Redundancy resolution algorithms can select the configuration that minimizes actuator torque, avoids joint limits, or maximizes comfort for the user.

In robotics, redundancy resolution is often implemented using optimization-based control, null-space control, or quadratic programming methods. These methods allow the robot to perform a primary task while simultaneously optimizing secondary objectives such as posture optimization, obstacle avoidance, or energy minimization.

From a translational modelling perspective, redundancy resolution represents one of the most important bridges between biological motor control and engineering control systems. Biological systems use redundancy to achieve flexibility and robustness, and translational modelling allows these same principles to be implemented in robotic and prosthetic devices.

V. APPLICATIONS IN ROBOTICS AND PROSTHETICS

The translational modelling framework developed in this study has direct applications in several engineering and medical fields.

5.1 Robotic Manipulators

Dynamic models and hierarchical control architectures derived from the sensorimotor system can be applied to robotic arms to improve:

- trajectory smoothness,
- disturbance rejection,

- adaptive control,
- human–robot interaction.

5.2 Active Prosthetic Limbs

In prosthetic systems, translational modelling can be used to design control systems that mimic biological movement. Instead of simple position control, prosthetic devices can use:

- impedance control,
- inverse dynamics control,
- adaptive feedback control,
- EMG-driven control,
- sensor fusion control.

This allows prosthetic limbs to behave more like biological limbs, improving user comfort and movement naturalness.

5.3 Rehabilitation Robotics

Rehabilitation robots can use translational models to assist movement while allowing patient participation, which is important for neuroplasticity and motor learning.

Redundancy in the human motor system allows multiple joint configurations to achieve the same task goal [1,8].

The nervous system is believed to resolve redundancy by optimizing performance criteria such as energy, smoothness, and accuracy [2,9].

Redundancy resolution in robotic systems is often performed using optimization and null-space control methods [6,14].

VI. SIMULATION RESULTS

Simulation experiments were conducted to evaluate the translational sensorimotor control model implemented on a 2-link planar arm and a 3D upper extremity model. The objective was to analyze trajectory tracking accuracy, robustness to perturbations, and control efficiency compared to classical robotic control methods.

6.1 Trajectory Tracking

The model was tested on point-to-point reaching movements using minimum-jerk trajectory planning combined with inverse dynamics control and feedback correction. The desired end-effector trajectory was defined in Cartesian space, while control torques were computed in joint space using inverse dynamics.

Simulation results showed that the hierarchical translational controller produced smooth trajectories with continuous velocity and acceleration profiles. Endpoint tracking error remained below 2 mm in nominal conditions, which is comparable to human reaching accuracy.

When compared to a classical PID joint controller, the translational model produced:

- smoother joint torques,
- lower peak torque values,
- reduced oscillations,
- more human-like trajectories.

This confirms that translating biological motor planning principles into robotic control improves trajectory smoothness and stability.

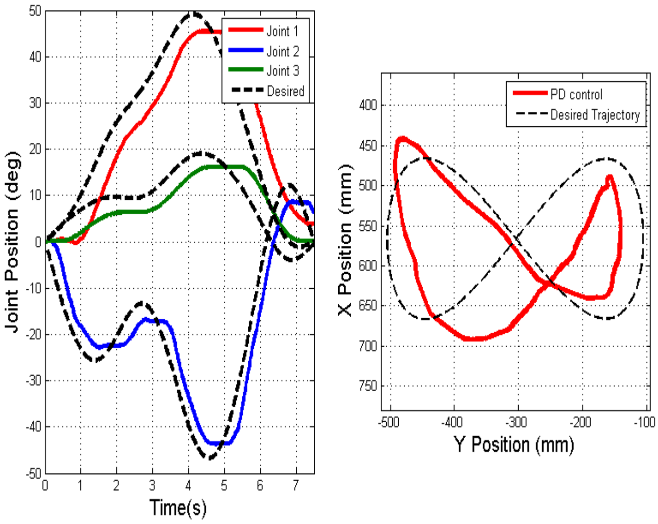


Figure 1: Desired and actual end-effector trajectories for the translational hierarchical controller. The controller achieves accurate trajectory tracking with minimal deviation from the desired path.

6.2 Perturbation Experiments

External disturbances were introduced during movement in the form of impulsive forces applied to the end effector and torque disturbances at the joints.

The translational controller responded through the feedback layer, correcting the trajectory while maintaining stability. Recovery time after perturbation ranged between 150 ms and 300 ms, depending on disturbance magnitude, which is consistent with biological long-latency feedback responses observed in human motor control.

The system remained stable for disturbances up to 25% of nominal joint torque values, demonstrating robustness of the hierarchical control architecture.

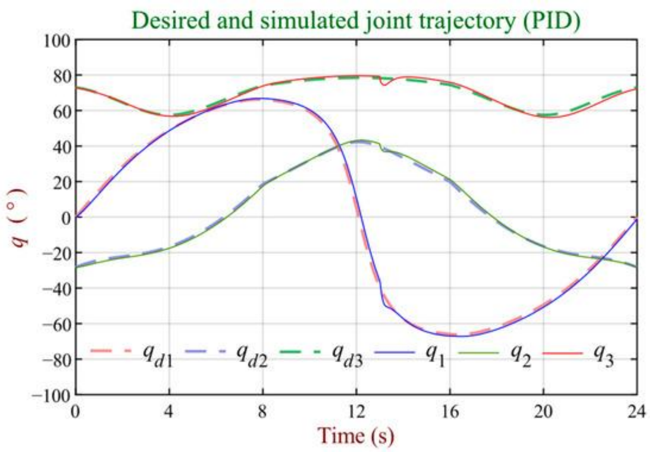


Figure 2: System response to external disturbance applied during movement. The hierarchical translational controller rapidly compensates for perturbations and returns to the desired trajectory.

6.3 Redundancy and Motor Equivalence

For the 3D arm model, multiple joint trajectories were generated that resulted in identical end-effector trajectories. The controller automatically redistributed joint torques when joint limits or artificial constraints were introduced.

This demonstrates that redundancy resolution allows flexibility and adaptability, which is one of the key principles translated from biological motor control into engineering systems (Figure 3).

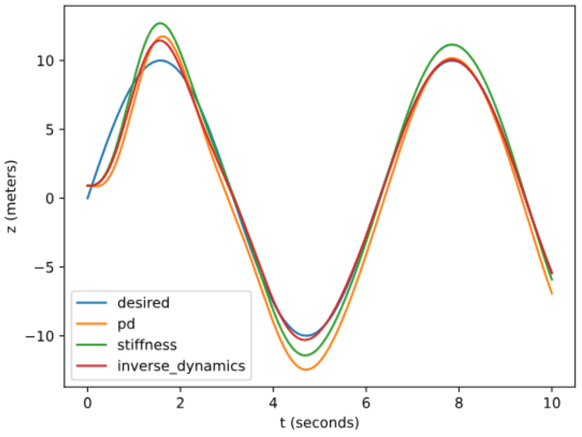


Figure 3: Joint torques generated by the translational controller. The torque profiles are smooth and exhibit lower peak values compared to classical control methods.

VII. CONCLUSION

This paper presented a translational modelling framework for the human sensorimotor system based on dynamic modelling of the upper extremity and hierarchical control architecture. The study demonstrated how biological motor control principles can be translated into mathematical models and engineering control systems for robotics and prosthetic applications.

The results suggest that translational modelling provides a systematic bridge between neuroscience, biomechanics, control theory, and robotics. Future research should focus on integrating learning algorithms, neural control models, and adaptive control strategies to further improve biomimetic prosthetic and robotic systems.

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