# Guest Editorial Special Issue on Movement Sciences in Cognitive Systems

Movements play a critical role in robotic systems, with considerations varying across different robotic systems regarding factors such as accuracy, speed, energy consumption, and naturalness of movements in various parts of the robotic mechanics. Over the past decades, the robotics community has developed computationally efficient mathematical tools for studying, simulating, and optimizing movements of articulated bodies to address these challenges.

Generating suitable movements and adapting to changing environments pose significant challenges for cognitive systems. To address these challenges, novel sensing technologies and accompanying algorithms are required to enable robots to perceive their environments and interact with human counterparts. By drawing inspiration from biological principles that underlie adaptive and learning strategies in animals and humans, new robotic technologies and cognitive system designs can be developed. Observing and analyzing the mechanisms of perception and action in biological systems can facilitate the development of more agile and natural behaviors in robotic systems. For example, the complex brain circuitry responsible for movement control, including muscle contraction, highlights the importance of neural structures such as the spinal cord, cerebral cortex, basal ganglia, and cerebellum in enabling adaptation and flexibility of movements in humans and other mammals. The mechanism of reinforcement learning from supraspinal control is essential for understanding human locomotion control.

Hence, this special issue on movement sciences in cognitive systems focuses primarily on the impact of various computational aspects of movement sciences on the development of intelligent systems. Within cognitive systems, findings and methodologies derived from the analysis of human or animal motion in fields such as biomechanics, neuroscience, computer graphics, and computer vision are quickly being integrated into various applications, including rehabilitation robots, ergonomic designs, and assistive robots.

We are also interested in practical applications. these bio-inspired novel techniques are being employed in increasingly complex mechanical structures, particularly those designed to adapt to their users, such as prosthetics and artificial systems used in rehabilitation and sports training. This quantitative analysis and synthesis of biological motion are expected to enable broader applications in fields such as medical diagnosis, monitoring and providing feedback for physical training, animation, ergonomic analysis and design, as well as the development of assistive robots and devices.

Therefore, to provide a platform for multi-disciplinary researchers to share their research from the perspectives mentioned above, we have organized a special issue on movement sciences in IEEE Transactions on Cognitive and Developmental Systems (TCDS). The guest editors and their invited reviewers have critically evaluated the originality, quality, and relevance of all submitted papers. Through a rigorous and meticulous review process, we have selected 8 high-quality papers for publication. These papers highlight scientific findings from movement neuroscience, algorithms developed for analyzing, simulating, and optimizing articulated body movement, and their applications in learning and interpreting complex structures or movements in cognitive systems.

By integrating tactile feedback into robotic systems, intelligent machines can enhance their ability to interact with and navigate through complex surroundings, ultimately improving their overall performance and versatility. In A1, Lu et al. introduce a novel bio-inspired tactile sensor with multifunctional capabilities and varying sensitivity across contact areas. One area on the sensor is highly sensitive, which can be used for object classification upon direct contact, while the other area is with lower sensitivity which can be served to localize side contact areas. By linking tendons with these two areas, the sensor can perform multiple detection functions within the same region. To process mixed contacting signals from the region, marked with numerous markers and pins, they employ a modified DenseNet121 network. This network removes all fully connected layers while preserving the rest as a sub-network. Additionally, the proposed model includes a global average pooling layer with two branching networks to handle different functions and provide accurate spatial translation of the extracted features. Moreover, the new tactile sensor is employed for obstacle avoidance. Action skills are extracted from human demonstrations, and an action dataset is generated for reinforcement learning, guiding robots toward correct responses after contact detection.

Assisting humans in collaborative tasks is a promising application for robots, yet effective assistance remains challenging. In A2, the authors introduce a method for providing intuitive robotic assistance based on learning from natural human limb coordination. To capture the coupling between multiple-limb motions, a fuzzy inference system for modeling trajectory adaptation is proposed. The associated polynomial coefficients are estimated using a modified recursive least squares method with a dynamic forgetting factor. Additionally, the authors propose employing a Gaussian process to generate robust predictions of human motion, thus mitigating uncertainty and measurement noise in interactive environments. Experimental results on two types of interaction tasks demonstrate the effectiveness of this approach, achieving high accuracy in predicting assistive limb motion and enabling humans to perform bimanual tasks using only one limb.

The models of human behavior's position and stiffness can act as reference profiles for robotic movements, enabling robots to perform physical tasks through impedance control that mimics human behavior. However, studies have shown that variable stiffness parameters in the impedance controller can violate the passivity constraint of robot states, leading to unsafe human-robot interactions where the robot's stored energy exceeds the external energy input from the human user. To address this issue, Cao et al. in A3 provide an approach by combining model predictive control and impedance control to enable compliant and safe robot interaction with humans. They propose a novel passive model predictive impedance control method with two control loops. The passivity of the closed-loop robot system and the feasibility of MPC are guaranteed by theoretical analysis, ensuring safe robotic movement in human-robot interactions.

The paper A4 from Huang et al. introduces a method for path learning in physical human-robot interaction (pHRI) using a stretch-compression iterative learning control (ILC) scheme and contouring impedance control. The robot learns a desired task path from the human user via a kinaesthetic interface and provides physical assistance during repetitive interactions and deals with various human uncertainties. The proposed ILC approach, based on stretch and compression operations, addresses repetitive learning processes with varying periods and accommodates uncertain human speeds during collaboration with a robot. It accommodates the varying time durations of each iteration due to uncertainty in the human user's force and motion.

In dexterous manipulator teleoperation, gestures can be used to control the manipulator's movements and actions. These gestures are often mapped to specific commands or motions, allowing operators to intuitively control the manipulator's actions remotely. Paper A5 presents a lightweight 3D hand pose estimation method from depth images called Biomechanical Structure Information-based Convolutional Network (BaSICNet), which is also applied to dexterous manipulator teleoperation. BaSICNet utilizes a cascade structure that incorporates hand biomechanical information, consisting of a two-stage cascade model. The first-stage module, CrossInfoNet, separates fingers and palm, while the second-stage cascade further separates each finger. Biomechanical-constraint loss functions, including local and global bone length loss, local and global bone angle loss, and palm angle loss, are proposed to enhance 3D hand pose accuracy.

Reinforcement learning (RL) in the brain involves the process by which the brain learns to associate specific actions with rewards or punishments, guiding future decision-making and behavior. In applications, there has been a growing interest in Cooperative Multi-Agent Deep Reinforcement Learning (MADRL), which has found applications in computer games and coordinated multi-robot systems. However, achieving high solution quality and learning efficiency in MADRL under conditions of incomplete and noisy observations remains challenging. Paper A6 introduces a novel approach called Grouped Cognitive featurE representatioN (GCEN) for multi-agent deep reinforcement learning, following the Centralized Training and Decentralized Execution (CTDE) paradigm. GCEN incorporates a grouped attention mechanism and a training approach using mutual information to improve learning efficiency and solution quality.

A study on human-robot interaction involving the robot's motor actions and behaviors was conducted to investigate how various factors affect people's intuitive understanding of expressive nonverbal robot movements, by measuring the mental effort exerted by users. The study in A7 by van Otterdijk et al. hypothesized that the robot's appearance, viewing angle, and expressions would affect the mental effort needed to understand its movements. Fifty participants were asked to watch eighteen short video clips featuring three different types of robots performing expressive behaviors, while their pupil response and gaze were measured using an eye tracker. The results indicate that all these factors influenced participants' mental effort and, consequently, their intuitive understanding of the robot's motion. One possible explanation for these findings is that social robots are instinctively perceived similarly to humans and animals, eliciting comparable mental effort responses during interaction.

Active Inference offers a framework for understanding how humans control movement. It suggests that movement control involves continuously updating internal predictions based on sensory information to minimize prediction errors. This process allows humans to adaptively select and execute actions that are aligned with their goals and expectations, even in the presence of uncertainty and noisy sensory inputs. By integrating sensory information with prior beliefs, Active Inference provides a coherent account of how the brain generates and regulates movement, offering insights into both normal motor control and motor disorders. The paper A8 provides a technical overview of Active Inference models in continuous time and explores how these models address various control problems, such as goal-directed reaching movements, active sensing, resolving multisensory conflicts during movement, and integrating decision-making with motor control. The unitary perspective of Free Energy has implications for understanding biological control mechanisms and designing artificial and robotic systems.

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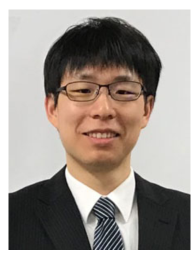
## APPENDIX: RELATED ARTICLES

A1 Z. Lu, Z. Zhao, T. Yue, X. Zhu, and N. Wang, "A bio-inspired multi-functional tendon-driven tactile sensor and application in obstacle avoidance using reinforcement learning," IEEE Transactions on Cognitive and Developmental Systems, 2023.
A2 Z. Wang, H. Fei, Y. Huang, Q. Rouxel, B. Xiao, Z. Li, and E. Burdet, "Learning to assist bimanual teleoperation using interval type-2 polynomial fuzzy inference," IEEE Transactions on Cognitive and Developmental Systems, 2023.
A3 Cao, L. Cheng, and H. Li, "Passive model predictive impedance control for safe physical human-robot interaction," IEEE Transactions on Cognitive and Developmental Systems, 2023.
A4 D. Huang, J. Xia, C. Song, X. Xing, and Y. Li, "Path learning by demonstration for iterative human-robot interaction with uncertain time durations," IEEE Transactions on Cognitive and Developmental Systems, 2022.
A5 W. Pang, Q. Gao, Y. Zhao, Z. Ju, and J. Hu, "Basicnet: Lightweight 3d hand pose estimation network based on biomechanical structure information for dexterous manipulator teleoperation," IEEE Transactions on Cognitive and Developmental Systems, 2022.
A6 H. Gao, X. Xu, C. Yan, Y. Lan, and K. Yao, "Gcen: Multi-agent deep reinforcement learning with grouped cognitive feature representation," IEEE Transactions on Cognitive and Developmental Systems, 2023.
A7 M. van Otterdijk, B. Laeng, D. S. Lindblom, and J. Torresen, "The effect of expressive robot behavior on users' mental effort: A pupillometry study," IEEE Transactions on Cognitive and Developmental Systems, 2024.
A8 M. Priorelli, F. Maggiore, A. Maselli, F. Donnarumma, D. Maisto, F. Mannella, I. P. Stoianov, and G. Pezzulo, "Modeling motor control in continuous-time active inference: a survey," IEEE Transactions on Cognitive and Developmental Systems, 2023.

**Junpei Zhong** Junpei 'Joni' Zhong earned his Ph.D. degree from the Department of Computer Science at the University of Hamburg, Germany. Prior to this, he obtained M.Phil and B.Eng degrees from the Hong Kong Polytechnic University and South China University of Technology, respectively. Currently serving as a Research Assistant Professor with the Hong Kong Polytechnic University, Dr. Zhong specializes in machine learning, robotics, and cognitive science. His research endeavors are dedicated to the development of human-centric AI systems, focusing on innovative applications such as data-driven disease reminders, adaptive devices, and assistive robots for elderly. These pioneering initiatives are poised to bring substantial benefits to the ageing society in both Hong Kong and mainland China.



**Ran Dong** earned his Ph.D. in Engineering, majoring in Computer Science, from the Graduate School of Systems and Information Engineering at the University of Tsukuba, Japan, in 2020. From April 2020 to March 2023, he served as an Assistant Professor at the School of Computer Science at Tokyo University of Technology. He is currently a Lecturer at the School of Engineering at Chukyo University, Japan. His research has focused on human-machine interaction and artificial intelligence. Currently, he is involved in projects related to motion design and control using deep learning.

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