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Development and iterative learning-enhanced sliding mode control of a bioinspired knee exoskeleton

Key words: Human–machine misalignment; Knee exoskeleton; Sliding mode control; Iterative learning control

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Motivation

Traditional knee exoskeletons designed as simplified single hinges fail to replicate the human knee’s complex polycentric motion. This simplification frequently causes severe human–machine kinematic misalignment, leading to user discomfort and secondary joint injuries. Existing self-aligning mechanisms (e.g., four-bar linkages or complex pulleys) significantly increase structural complexity, weight, and mechanical impedance. Human–exoskeleton coupled dynamics are highly nonlinear, causing traditional or purely reactive controllers to suffer from severe tracking lags and chattering.

Main idea

- Develop a novel biomimetic knee structure integrating the anatomical “optimal axis of rotation” with a dynamic pin–cam tracking profile.
- Incorporate a highly integrated, lightweight quasi-direct drive (QDD) system with elastic units to provide transparent assistive torque.
- Propose a unified iterative learning (IL)-enhanced sliding mode control (SMC) strategy to perfectly synergize periodic gait learning with robust instantaneous impact rejection.

Method

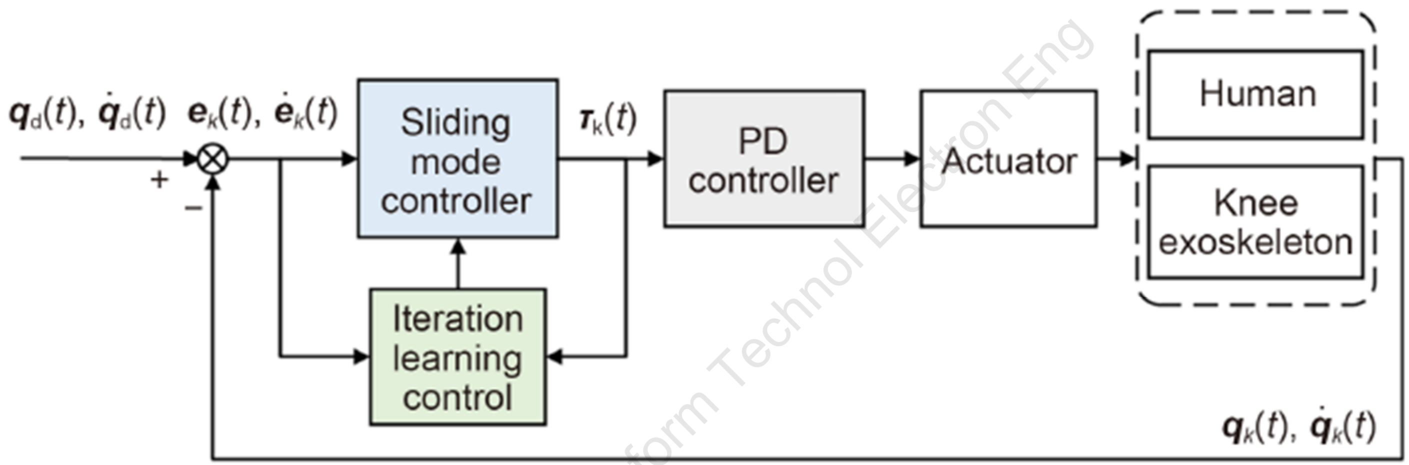


Fig. 6 Control diagram of the knee exoskeleton (PD: proportional–derivative)

Results

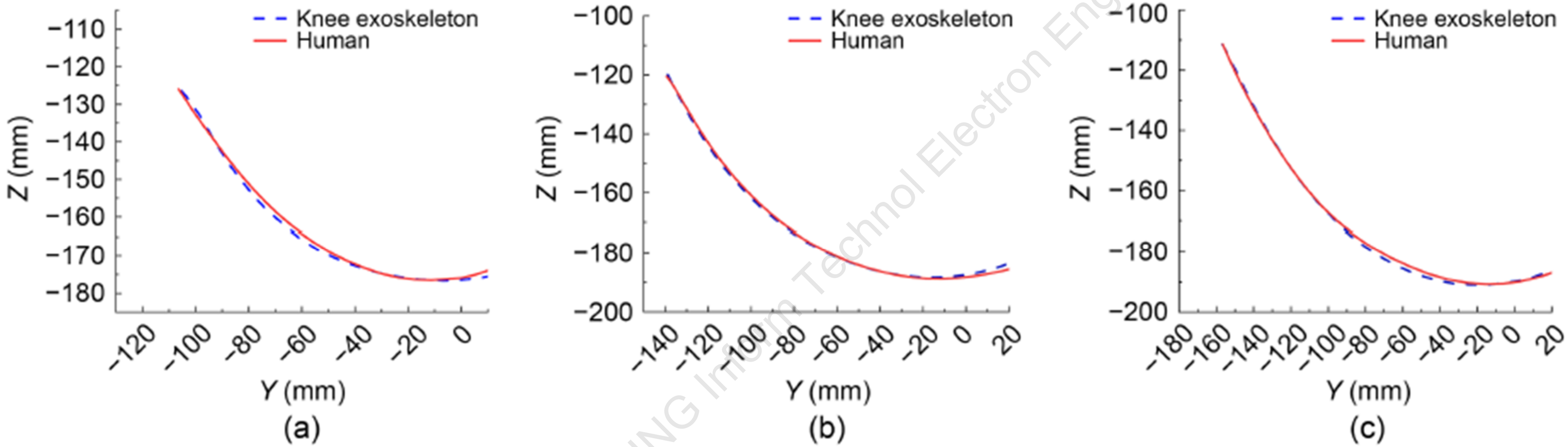


Fig. 8 Comparison of human–exoskeleton joint trajectories: (a) subject 1; (b) subject 2; (c) subject 3

Results

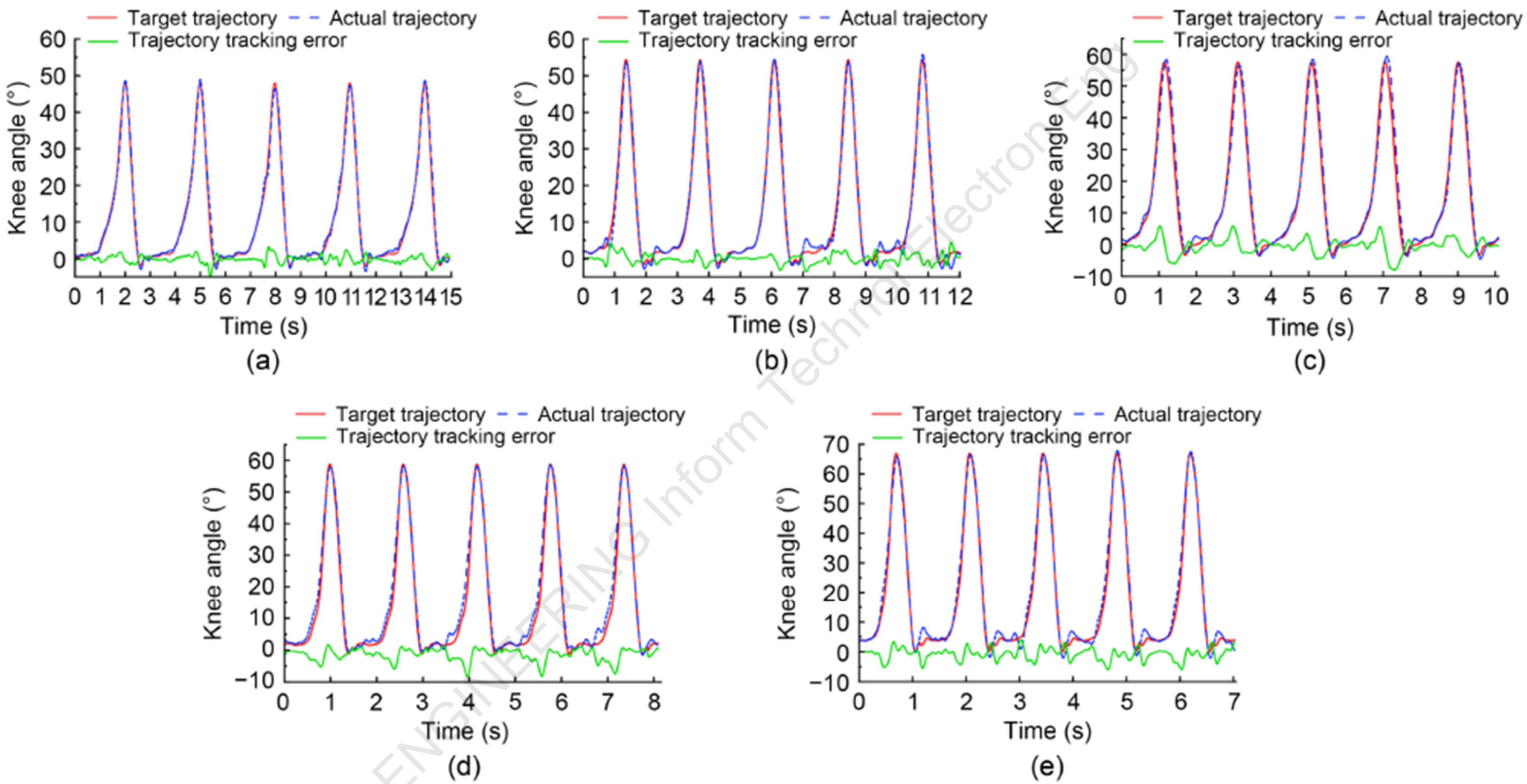


Fig. 10 Human–exoskeleton trajectory tracking results of the proposed IL-enhanced SMC at different speeds: (a) 1 km/h; (b) 1.5 km/h; (c) 2 km/h; (d) 2.5 km/h; (e) 3 km/h

Results

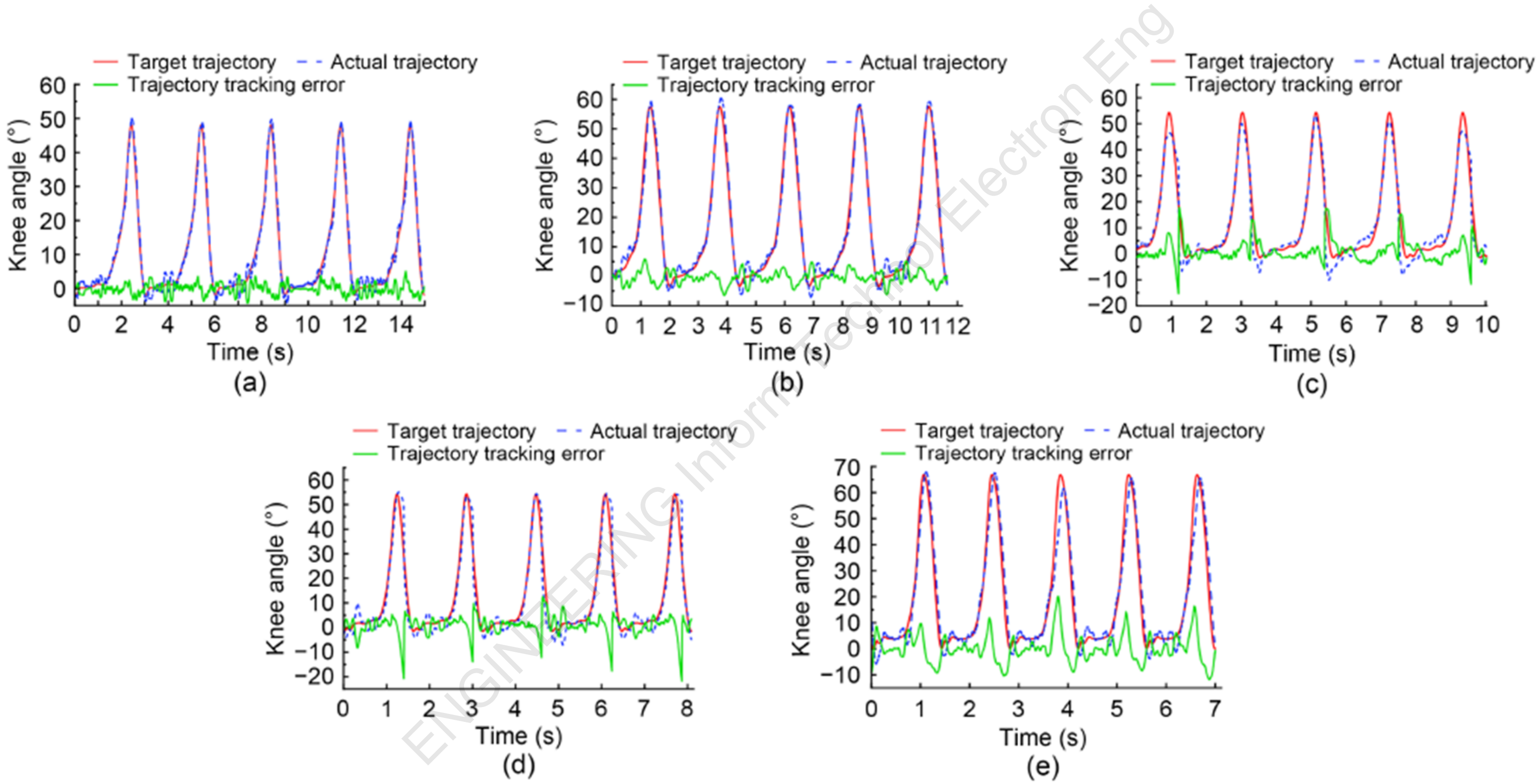


Fig. 11 Human–exoskeleton trajectory tracking results of PID control based on iterative learning at different speeds: (a) 1 km/h; (b) 1.5 km/h; (c) 2 km/h; (d) 2.5 km/h; (e) 3 km/h

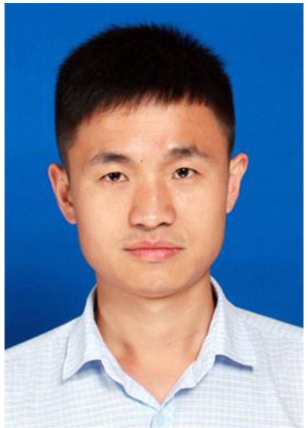
Results

Table 3 Comparison of tracking errors under different control methods and walking speeds

Control method	Error type	Error value (°)				
		1 km/h	1.5 km/h	2 km/h	2.5 km/h	3 km/h
Proposed IL-enhanced SMC	RMSE	1.05	1.34	2.51	2.46	2.16
	Maximum error	4.93	4.32	7.92	8.37	5.98
PID based on iterative learning	RMSE	1.65	2.32	4.38	4.14	5.40
	Maximum error	5.04	6.54	17.77	21.70	20.14

Conclusions

- The proposed biomimetic structure effectively eliminates human–machine joint misalignment, ensuring seamless kinematic compatibility.
- The IL-enhanced SMC strategy perfectly synergizes periodic learning with robust disturbance rejection, without requiring massive computational overhead.
- The hardware–software synergy presents an effective, robust, and computationally efficient robotic-assisted strategy for restoring natural walking ability.



Yi LONG received the B.S. degree in mechanical engineering from Sichuan University, Chengdu, China, in 2010, the M.S. and Ph.D. degrees in mechanical engineering from Harbin Institute of Technology, Harbin, China, in 2012 and 2017, respectively. He is currently an associate professor in the Faculty of Robot Science and Engineering, Northeastern University and Foshan Graduate School of Innovation, Northeastern University, Foshan, China, where he leads a lab focusing on robotics technology and machine vision. His current research interests include wearable exoskeletons, mobile robots, machine learning, and computer vision.