Guest Editorial
An Overview of Biomedical Robotics and Bio-Mechatronics Systems and Applications

I. Introduction

THE studies on bio-mechatronics systems and applications have been carried out for more than three decades, to overcome the challenges raised from both theoretical and experimental sides, especially those posed by the application of mechatronics and robotics in healthcare and medical fields. The research on biomedical robotics and bio-mechatronics covers a diverse spectrum of rapid rising interdisciplinary areas including bio-inspired robots for industrial, military, medical, and rehabilitation applications. This special issue aims at showcasing the most exciting and recent advances in the application of robotics and mechatronics in various fields and brings together a broad spectrum of topics covering various definition, development, control, and deployment of bio-mechatronics/robot systems, including social robots, wearable robot systems such as exoskeleton, rehabilitation robot, tele-robot, and a numbers of systems engineering approaches such as modeling, optimization and control. This special issue is to give analysis to the biological systems from a "bio-mechatronic" point of view, and to investigate the engineering and scientific principles behind their remarkable performance. High-quality original papers of innovative ideas and concepts have been included in the special issue of biomedical robotics and bio-mechatronics systems and application. While the design and development of bio-inspired machines and systems with novel and high performance in various applications have been investigated as well. The recent development of multidisciplinary research shall contribute to the promotion of the research on biomedical robotics and bio-mechatronics systems and application, with application to transportation, diagnosis, surgery, assistive technology, prosthetics, personal assistance, rehabilitation, health care, in laboratory, hospital, and the real world.

In this issue, we bring our attention to two specific intertwined requirements which are necessary to achieve this vision: one is the engineering and scientific principles underlying the extraordinary performance of biomedical robotics and bio-mechatronics; and the other is the application of the principles to design the corresponding algorithms that purposively operate in dynamic scenarios.

II. Biomedical Robotics and Bio-Mechatronics Systems

Research activities in biomedical robotics and bio-mechatronics systems tracks back to the 1970s and 1980s. With remarkable discipline crossing features, biomedical robotics and bio-mechatronics systems nowadays become a hot area for technological and scientific investigation. Their methodological background originated from the biomedical engineering and robotic sectors, while now their application scope moves toward various engineering departments, as well as fundamental and applied science including biology, neuroscience, medicine, and even toward humanities such as sociology, ethics, and philosophy.

Acquisition of the knowledge of the working mechanism behind the biological systems is the one of the main purposes of the studies of biomedical robotics and bio-mechatronics systems. As a result, analysis of the biological systems is often performed from a "biomechatronic" point of view. The knowledge is utilized to develop innovative technologies and methodologies that could lead to design and building of bio-inspired machines and systems by mimicking insects, animals, humans, and various living beings. The combination of robotic technology with in-depth biomedical sciences is also promising for future generation of biomedical devices and applications.

A biomedical robotics and bio-mechatronics systems based approach is of great interest, and its three main goals include: 1) enhancing the understanding of the underpinning mechanisms of sensing and actuating in various creatures including our humans; 2) building valid and useful mechatronic and robotic systems of high performance; and 3) developing effective interactive biological systems, e.g., therapy technology.

The interest of research toward this direction is evidently increasing in the strong growth of activities in: 1) humanoid robotics; 2) bio-inspired and bio-mimetic robotics; 3) human–robot interaction and cooperation; and 4) bio-mechatronic devices for endoscopy, surgery, assistance, and rehabilitation. The large number of implementations of mechatronics and robotics in various fields, as well as the increasing interest of biological inspiring design in the progresses of artificial systems, raise new challenges on both theories and technologies. It is very important to deeply reconsidered the technologies and models which used in the design and fabrication of biomechatronic devices and bio-inspired robots for further progress.

These issues that impact on biomedical robotics and bio-mechatronics systems are collected, organized in locomotion principles (in terms of sensing, dynamics, control, and actuation) of biological systems in underwater, land, and air; the physical design of their bodies; and the organization of their nervous and sensory systems.

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III. Challenges

According to the above discussion, we see that there are clearly a great deal of significant challenges that must be faced in the studies of biomedical robotics and bio-mechatronics systems and its applications.

A. Bio-Inspired Locomotion and Mechanisms

We could improve locomotion mechanism based on a thorough understanding of the behavior characteristics of various creatures, e.g., leg coordination mechanisms in the walking stick insect is used to control a hexapod robot walking straightly in [1]. In [2], the so called whole skin locomotion inspired by the movement of single celled organisms was developed. It works with an elongated toroid to generate the overall motion of the cytoplasmic streaming, and thus turns itself inside out in a single continuous motion. And with more capable and representative element and material models, it can perform even more fluently. Zhou and Low [3] developed a robotic manta ray as a biologically inspired underwater vehicle for potential marine applications. In [4], a biomimetic fish-like micro robot using novel actuator was developed for a micro robot swimming structure in water medium with a buoyancy adjuster and a propulsion tail fin. In [5], an autonomous robotic fish was developed for 3-D locomotion, by employment of a situated-behavior-based decentralized control structure on each robotic fish according to its visual data.

Considerable effort has been devoted to improve the physical capabilities of legged mobile robots. For examples, electrically driven humanoid (e.g., Honda's ASIMO [6], Toyota Humanoid [7], and HRP series [8]) with high control gains have demonstrated impressive motion planning and execution. Highly elaborated quadrupedal robots like MUTANT [9], Boston Dynamics' Big Dog [10], MIT Cheetah Robot [11], and the research platform HyQ [12] are hydraulically actuated similar to some of the most advanced humanoid robots.

The exoskeleton robots are developed to particularly augment the our human natural muscular force for carrying heavy loads. Compared with rehabilitation exoskeletons which recover the neuro-musculoskeletal function of stroke or post-surgical patients, assistive exoskeletons can assist the elderly or individuals with mobility disorders. In recent literature, a number of exoskeleton robotic legs have been developed and investigated mainly focusing on two different applications. We categorize these studies into two types: 1) enhancement of walking over a long distance or increasing load capability to carry heavy load repetitively [13], [14] and 2) rehabilitation aids for gait disorder persons or aged people [15], [18], [19]. Elderly people or gait disorder patients may lose muscular strength in their legs and become bedridden. The lower exoskeleton attached to their legs is hoped to enhance their muscular strength and to restore their walking abilities as normal people [20]. For example, in [16], the upper limb exoskeleton robot was developed and adaptive backstepping control using fuzzy approximation was designed to assist forearm movement that would enable a human forearm to track any continuous desired trajectory. In [17], considering the same upper limb exoskeleton robot, fuzzy approximation and disturbance observers was designed for compensating various dynamic errors and uncertainties.

On the other side, robotic bionic arms and prosthesis hands/legs become very useful for people with severe physical disabilities, as they are able to support disabled achieving greater independence and thereby increase their quality of life [21]–[23]. A compact bionic handling arm was developed in [24], and it could reproduce biological behaviors of trunks, tentacles, or snakes. In [25], a developed multifingered dexterous hand with flexible tactile skin was presented, which has five fingers with 6-degrees of freedom (DOFs), and each finger is equipped with a small harmonic drive gear and a fine high-power mini actuator, and each fingertip is covered with the tactile array sensors for determination of the force between the finger and the grasped object. In [27], EMG signals were decoded with a pattern recognition algorithm for a prosthesis leg and combined with data from sensors to interpret the patient's intended movements.

Generally, the development of bio-inspired applications should follow the development of biological mechanical design, so that we can imitate the mechanisms more naturally. On the other hand, we should obtain deeper acquaintance of the behavior structure and characteristics of the imitated biology, and perform more thorough analysis on the dynamics of locomotion system. In addition, to improve the performance of robotic locomotion, it is necessary to modify the existing the models of the bio-inspired locomotion and apply optimization techniques on them. Moreover, the new technology in practical applications will also generate new challenges, such as the limited carrying ability and stability.

B. Bio-Inspired Sensing/Actuation

Human arm muscles are of highly hierarchical fibrillar structures with parallel and distributed actuation architecture, and thus have advanced properties such as high power density, high strain, high stresses, high efficiency, stiffness tuning capability, high strain rates, multifunctionality, high durability, self-sensing capability, and self-repairing capability [26].

The purpose of investigating bio-inspired sensing/actuation is to discover the underlying principles of the biological sensing and actuating systems, to understand the architectural design of human arm muscles, to develop graphical and analytic models of tendons, muscles as well as the joints, and to recognize the factors that affect strength recovery in humans following surgical tendon transfer and the cellular events associated with adaptation of muscle to manipulation.

Development of soft muscle-like actuators with similar properties has been a long-term goal for a generation of researchers. An actuator containing a pneumatic force generator was introduced in [28]. The force generator is on one side in parallel with a nonlinear damping element and on the other side in series with a nonlinear elastic "tendon." An effective fabrication method for cylindrical ionic polymer metal composite actuators was developed in [29] with application to 2-DOF bending, and a better performance could be obtained by optimization of the model. Different from rigid actuators, the serial elastic actuator (SEA) contains an elastic element series connect with the mechanical power source. There are several unique properties of SEAs using elastic element compared with rigid actuators, e.g., tolerance to impact loads, low mechanical output impedance, passive mechanical energy storage, and increased peak power output [30], [31]. The SEA concept was extended by variable stiffness actuators with an additional DOF, so it is capable to adjusting the stiffness of passive elastic mechanically [32]–[36]. Other SEA implementations have experimented to maximize energy storage with nonlinear spring stretching [37].

Muscle contraction causes motion of the corresponding limb, while the muscle activity can be detected by EMG device, from which the signals can be used to decode the manipulation intention of the user. EMG signals can be utilized in cases where an exoskeleton is need to fulfill daily tasks. Therefore, the EMG signals might be chosen as control interfaces for the robotic exoskeleton, moreover, the recording method does not increase any bulky mechanisms on the user [44], [45].

Our human muscular skeleton systems constantly receive information from brain to govern the body motion. To detect the neural control commands, brain signal acquisition system based on electroencephalogram (EEG) systems was developed. The function of the established brain machine interface (BMI) is usually to detect a user's motion intention, which can be then sent to the controller. To augment the information gathered from EEG-based systems, additional sensors may be utilized to provide supplementary information, that can be fused together to enable a better interpretation of the user's intent. This is especially important in times when the EEG-based system is unable to provide sufficient information in a timely manner. Recent studies on BMI-based control have achieved considerable progress, e.g., primates and humans are able to control prosthetic devices via a BMI [38], [39], [40], [41], where electroencephalographic (EEG) signals measured by noninvasive surface electrodes play an important role. The BMI has been conventionally categorized as evoked and spontaneous. In comparison to spontaneous BMIs that are far from application to perform complex tasks, evoked BMIs reflecting the automatic response to certain external stimuli [39], [40] are more ready for complex tasks, especially for motion of multiple DOFs.

To advance bio-inspired sensing and actuating technologies, it is necessary to further develop new materials and biotechnology. In addition, some modification of the existing model and application some optimization techniques on the controlling process is expected. Moreover, the implement of proposed design is accompanied by unknown challenges.

C. Bio-Inspired Control Design

To develop new kinds of bio-inspired control systems, it is critical to first understand the mechanisms by which the efficiency, motion performance, and safety are obtained by biological systems. Our neuromuscular control system enables us to manipulate tinny objects skillfully, and to perform fast movements. It also enables us to move using eight times less energy when we walk than when we take the train, and to move in the most efficient way using a bicycle. It is also worth to mention that our humans or primates perform adaptive motions naturally without considering their kinematic configurations against unexpected disturbances or environment changes. However, it remains a challenge to understand the way in which the motion is controlled and learned by the neuromotor system to exploit these underlying physical properties. Neuromotor experimental studies have shown that the impedance of the human joints can be voluntarily adapted during motion. If the delicate impedance adaptation skills of human operator can be incorporated into robot control, it would greatly benefit the physical human–robot interaction [46]. It is well known that the limb endpoint visco-elastic properties can be regulated by the relevant muscles and the pose configuration in different ways. In [47], the regulation can be achieved by co-contracting muscles acting on the limb, and it can be acquired as well through the adaptation in the sensitivity of reflex feedback [48], or the selective control of limb configuration [49]. In [50] and [51], a position perturbation was implemented to the hand, and the related forces and displacement were acquired and recorded by the specified device. Then, the impedance parameters were estimated by undergoing a post-processing stage. In [52], the estimation of dynamic impedance profiles using perturbation based methods in multijoint arm movements has been widely studied. However, perturbation-based approaches are hard to implement in the real-time manipulation, for the intrusion of the external disturbance. Consequently, some suitable human–machine interface has been investigated for real-time applications [53]–[55].

IV. Guide to This Special Issue

This special issue includes the papers at various levels and in various forms, which try to find the solutions for most challenges mentioned in the previous section, and we believe they all contribute toward a better understanding of bio-inspired mechatronic and robotic systems in the three aspects mentioned above.

In developing new bio-inspired locomotion and mechanisms, a wearable, portable, low-cost, and easy-to-use upper extremity exoskeleton robot design for clinical and in-home therapies of patients is presented in [56]. The robot has 5-DOFs with safe pneumatic muscles and the subjects also expressed enthusiasm regarding the system. The clinical and in-home trials of chronic stroke subjects has proved its validity. In [57], considering the dynamics modeling and identification of iLeg, the traditional methods are insufficient. For solving this, in the work of, a method for recognition of patients'motion intention is proposed. First, the coupling factors among the joints are described in the friction model by using the empirical formulation. Then, an IRG strategy is designed to efficiently search the valid initial solutions of the optimization problem for the exciting trajectories. Finally, the feasibility of the proposed methods is validated by several experiments.

In designing bio-inspired sensing/actuation, He *et al.* [58] proposed a wireless BCI-BMI system for an upper limb robotic arm. The EEG signals are processed via several wavelet denoising methods, common spatial pattern algorithm, and linear discriminant analysis algorithm. The extracted commands are sent to BCI subsystems to control the robot via a Bluetooth. The effectiveness of the methods have been tested by comparative simulations and experiments. Bhattacharyya *et al.* [59] investigated a BMI paradigm for control of a multijoint redundant robot system, which determines the direction of end-point movement of a 3-DOF robot arm using motor imagery EEG signal with co-adaptive decoder, and a synergetic motor learning algorithm was proposed to handle a redundancy in multi-DOF joints toward energy optimality through tacit learning. Zhao *et al.* [60] proposed a framework combining noninvasive EEG-based BCI with a noninvasive functional electrical stimulation, which can potentially enable the upper limbs to achieve more effective motor rehabilitation.

In the development of bio-inspired control design, a biological control system for 3-D locomotion of a humanoid biped robot is presented in [61], which involve four types of neurons: 1) motor neurons; 2) sensor neurons; 3) command neurons; and 4) gain neurons. A multiple-objective evolutionary algorithm was used effectively to construct the locomotion pattern by manipulating the weight of synapse between the motor neurons. In [62], a method for gait generation for biped robots omnidirectional walking on inclined ground was developed. The authors first built models for walking on an inclined ground. In the models, the angle of walking direction and the angle of elevation of the inclined ground were used for describing the motion of walking on an inclined ground uniformly. Their relationship between the sagittal and coronal planes were analyzed. Then, the authors used a DSP to generate gait. Then the motion trajectory of the robot center of mass is generated. In [63], a comprehensive vision-based crowd detection and GIS localization algorithm for a cooperative team of one unmanned aerial vehicle and a number of unmanned ground vehicles (UGVs) is present. The UGVs are used to convert the image locations of the detected targets into their GIS coordinates. And a testbed consists of real UVs and an agent-based simulation model is developed to conduct experiments. The authors had altered the key parameters of the system and studied their impacts on the system. The experimental results has prove the effectiveness of the algorithms. In [64], path planning problem for multi-AUV systems was investigated. In the planning method, a measurable model composed of multiple basis functions is defined to represent the scalar field. A selective basis function Kalman filter is developed to achieve model estimation through the information collected by multiple AUVs. In addition,the multidimensional rapidly exploring random trees star algorithm is proposed for the multi-AUV system. Finally, the method is demonstrated by simulation results and experiments in robotic fishes. In [65], object classification and grasp planning were investigated. On object classification, the authors use bag-of-system and deep dynamical system to complete the tactile perception and SHOT descriptor to model the shape of objects. Combining the tactile and vision perception, the authors proposed a fast planning method for grasping manipulation. Chan *et al.* [66] designed a feedforward neural network to build an NN-based human-pose estimation system. A mapping is first proposed that converts a Bayesian network to a feedforward NN, and then the system is built based on the proposed mapping that consists of two steps: 1) structure identification and 2) parameter learning. In [67], a kind of nonlinear biomechatronics system which bases on adaptive ensemble fifth-degree iterated cubature information filter was proposed. The four classic nonlinear fusion methods includes measurements fusion, weighted measurements fusion, sequential filtering fusion, and distributed filtering fusion. Their estimation performance are compared in this paper. The result shows that the proposed information filter can achieve higher level estimation accuracy and stability than the previous cubature Kalman filters.

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REFERENCES

[1] K. S. Espenschied, H. J. Chiel, R. D. Quinn, and R. D. Beer, "Leg coordination mechanisms in the stick insect applied to hexapod robot locomotion," *Adap. Behav.*, vol. 1, no. 4, pp. 455–468, 1993.

[2] D. W. Hong, M. Ingram, and D. Lahr, "Whole skin locomotion inspired by amoeboid motility mechanisms," *J. Mech. Robot.*, vol. 1, no. 1, pp. 677–682, 2005.

[3] C. Zhou and K. H. Low, "Design and locomotion control of a biomimetic underwater vehicle with fin propulsion," *IEEE/ASME Trans. Mechatron.*, vol. 17, no. 1, pp. 25–35, Feb. 2012.

[4] S. Guo, T. Fukuda, and K. Asaka, "A new type of fish-like underwater microrobot," *IEEE/ASME Trans. Mechatron.*, vol. 8, no. 1, pp. 136–141, Mar. 2003.

[5] Y. Hu, W. Zhao, and L. Wang, "Vision-based target tracking and collision avoidance for two autonomous robotic fish," *IEEE Trans. Ind. Electron.*, vol. 56, no. 5, pp. 1401–1410, May 2009.

[6] Y. Sakagami *et al.*, "The intelligent ASIMO: System overview and integration," in *Proc. Int. Conf. Intell. Robots Syst.*, vol. 3. Lausanne, Switzerland, 2002, pp. 2478–2483.

[7] R. Tajima, D. Honda, and K. Suga, "Fast running experiments involving a humanoid robot," in *Proc. IEEE Int. Conf. Robot. Autom.*, Kobe, Japan, 2009, pp. 1571–1576.

[8] H. Hirukawa, S. Kajita, F. Kanehiro, K. Kaneko, and T. Isozumi, "The human-size humanoid robot that can walk, lie down and get up," *Int. J. Robot. Res.*, vol. 24, no. 9, pp. 755–769, 2005.

[9] M. Fujita and H. Kitano, "Development of an autonomous quadruped robot for robot entertainment," *Auton. Robots*, vol. 5, no. 1, pp. 7–18, 1998.

[10] M. Raibert, K. Blankespoor, G. Nelson, and R. Playter, "BigDog, the rough-terrain quadruped robot," in *Proc. IFAC 17th World Congr.*, Seoul, South Korea, 2008, pp. 10822–10825.

[11] S. Seok *et al.*, "Design principles for energy-efficient legged locomotion and implementation on the MIT Cheetah robot," *IEEE/ASME Trans. Mechatron.*, vol. 20, no. 3, pp. 1117–1129, Jun. 2015.

[12] C. Semini *et al.*, "Design of HyQłA hydraulically and electrically actuated quadruped robot," *Proc. Inst. Mech. Eng. Part I J. Syst. Control Eng.*, vol. 225, no. 6, pp. 831–849, 2011.

[13] A. Tsukahara, Y. Hasegawa, and Y. Sankai, "Gait support for complete spinal cord injury patient by synchronized leg-swing with HAL," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Systems*, San Francisco, CA, USA, 2011, pp. 1737–1742.

[14] J. F. Veneman *et al.*, "Design and evaluation of the LOPES exoskeleton robot for interactive gait rehabilitation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 15, no. 3, pp. 379–386, Sep. 2007.

[15] J.-F. Zhang *et al.*, "5-Link model based gait trajectory adaption control strategies of the gait rehabilitation exoskeleton for post-stroke patients," *Mechatronics*, vol. 20, no. 3, pp. 368–376, 2010.

[16] Z. Li, C.-Y. Su, G. Li, and H. Su, "Fuzzy approximation-based adaptive backstepping control of an exoskeleton for human upper limbs," *IEEE Trans. Fuzzy Syst.*, vol. 23, no. 3, pp. 555–566, Jun. 2015.

[17] Z. Li, C.-Y. Su, L. Wang, Z. Chen, and T. Chai, "Nonlinear disturbance observer-based control design for a robotic exoskeleton incorporating fuzzy approximation," *IEEE Trans. Ind. Electron.*, vol. 62, no. 9, pp. 5763–5775, Sep. 2015.

[18] R. Lu, Z. Li, C.-Y. Su, and A. Xue, "Development and learning control of a human limb with a rehabilitation exoskeleton," *IEEE Trans. Ind. Electron.*, vol. 61, no. 7, pp. 3776–3785, Jul. 2014.

[19] L. Lünenburger, G. Colombo, and R. Riener, "Biofeedback for robotic gait rehabilitation," *J. Neuroeng. Rehabil.*, vol. 4, no. 1, pp. 1–11, 2007.

[20] E. Akdoğan and M. A. Adli, "The design and control of a therapeutic exercise robot for lower limb rehabilitation: Physiotherabot," *Mechatronics*, vol. 21, no. 3, 2011, pp. 509–522.

[21] J. Vogel *et al.*, "An assistive decision-and-control architecture for force-sensitive hand-arm systems driven by human–machine interfaces," *Int. J. Robot. Res.*, vol. 35, no. 6, pp. 763–780, 2015, doi: 10.1177/0278364914561535.

[22] R. D. Souza, S. El-Khoury, J. Santos-Victor, and A. Billarda, "Recognizing the grasp intention from human demonstration," *Robot. Auton. Syst.*, vol. 74, pp. 108–121, Dec. 2015, doi: 10.1016/j.robot.2015.07.006.

[23] C. Cipriani, M. Controzzi, and M. C. Carrozza, "The SmartHand transradial prosthesis," *J. Neuroeng. Rehabil.*, vol. 8, no. 29, pp. 1–13, 2011, doi: 10.1186/1743-0003-8-29.

[24] A. Melingui, O. Lakhal, B. Daachi, J. B. Mbede, and R. Merzouki, "Adaptive neural network control of a compact bionic handling Arm," *IEEE/ASME Trans. Mechatron.*, vol. 20, no. 6, pp. 2862–2875, Dec. 2015.

[25] G. Lin, Z. Li, L. Liu, H. Su, and W. Ye, "Development of multi-fingered dexterous hand for grasping manipulation," *Sci. China Inf. Sci.*, vol. 57, no. 12, pp. 1–10, 2014.

[26] T. J. Dawson and C. R. Taylor, "Energetic cost of locomotion in kangaroos," *Nature*, vol. 246, pp. 313–314, Nov. 1973.

[27] L. J. Hargrove *et al.*, "Robotic leg control with EMG decoding in an amputee with nerve transfers," *New England J. Med.*, vol. 369, no. 13, pp. 1237–1242, 2013.

[28] B. Hannaford, K. Jaax, and G. Klute, "Bio-inspired actuation and sensing," *Auton. Robots*, vol. 11, no. 3, pp. 267–272, 2002.

[29] S. J. Kim, D. Pugal, J. Wong, K. J. Kim, and W. Yim, "A bio-inspired multi degree of freedom actuator based on a novel cylindrical ionic polymer-metal composite material," *Robot. Auton. Syst.*, vol. 62, no. 1, pp. 53–60, 2014.

[30] G. A. Pratt and M. M. Williamson, "Series elastic actuators," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Pittsburgh, PA, USA, 1995, pp. 399–406.

[31] N. Paine, S. Oh, and L. Sentis, "Design and control considerations for high-performance series elastic actuators," *IEEE/ASME Trans. Mechatron.*, vol. 19, no. 3, pp. 1080–1091, Jun. 2014.

[32] J. W. Hurst, J. E. Chestnutt, and A. A. Rizzi, "The actuator with mechanically adjustable series compliance," *IEEE Trans. Robot.*, vol. 26, no. 4, pp. 597–606, Aug. 2010.

[33] T.-H. Huang, J.-Y. Kuan, and H.-P. Huang, "Design of a new variable stiffness actuator and application for assistive exercise control," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, San Francisco, CA, USA, Sep. 2011, pp. 372–377.

[34] N. G. Tsagarakis, I. Sardellitti, and D. G. Caldwell, "A new variable stiffness actuator (CompAct-VSA): Design and modelling," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, San Francisco, CA, USA, Sep. 2011, pp. 378–383.

[35] M. Grebenstein *et al.*, "The DLR hand arm system," in *Proc. IEEE Int. Conf. Robot. Autom.*, Shanghai, China, May 2011, pp. 3175–3182.

[36] A. Jafari, N. G. Tsagarakis, and D. G. Caldwell, "A novel intrinsically energy efficient actuator with adjustable stiffness (AwAS)," *IEEE/ASME Trans. Mechatron.*, vol. 18, no. 1, pp. 355–365, Feb. 2013.

[37] I. Thorson and D. Caldwell, "A nonlinear series elastic actuator for highly dynamic motions," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, San Francisco, CA, USA, Sep. 2011, pp. 390–394.

[38] M. A. L. Nicolelis, "Actions from thoughts," *Nature*, vol. 409, pp. 403–407, Jan. 2001.

[39] I. Iturrate, J. M. Antelis, A. Kubler, and J. Minguez, "A noninvasive brain-actuated wheelchair based on a P300 neurophysiological protocol and automated navigation," *IEEE Trans. Robot.*, vol. 25, no. 3, pp. 614–627, Jun. 2009.

[40] J. L. S. Blasco, E. Iañez, A. Ubeda, and J. M. Azorin, "Visual evoked potential-based brain-machine interface applications to assist disabled people," *Expert Syst. Appl.*, vol. 39, no. 9, pp. 7908–7918, 2012.

[41] L. R. Hochberg *et al.*, "Reach and grasp by people with tetraplegia using a neurally controlled robotic arm," *Nature*, vol. 485, no. 7398, pp. 372–375, 2012.

[42] L. R. Hochberg *et al.*, "Neuronal ensemble control of prosthetic devices by a human with tetraplegia," *Nature*, vol. 442, no. 7099, pp. 164–171, 2006.

[43] J. Duan, Z. Li, C. Yang, and P. Xu, "Shared control of a brain-actuated intelligent wheelchair," in *Proc. 11th World Congr. Intell. Control Autom.*, Shenyang, China, 2014, pp. 341–346.

[44] D. Tkach, H. Huang, and T. A. Kuiken, "Study of stability of time-domain features for electromyographic pattern recognition," *J. Neuroeng. Rehabil.*, vol. 7, no. 1, pp. 21–34, 2010.

[45] M. A. Oskoei and H. Hu, "Support vector machine-based classification scheme for myoelectric control applied to upper limb," *IEEE Trans. Biomed. Eng.*, vol. 55, no. 8, pp. 1956–1965, Aug. 2008.

[46] J.-S. Hu, J.-J. Wang, and D. M. Ho, "Design of sensing system and anticipative behavior for human following of mobile robots," *IEEE Trans. Ind. Electron.*, vol. 61, no. 4, pp. 1916–1927, Apr. 2014.

[47] P. L. Gribble, L. I. Mullin, N. Cothros, and A. Mattar, "Role of cocontraction in arm movement accuracy," *J. Neurophysiol.*, vol. 89, no. 5, pp. 2396–2405, 2003.

[48] K. Akazawa, T. E. Milner, and R. B. Stein, "Modulation of reflex EMG and stiffness in response to stretch of human finger muscle," *J. Neurophisiol.*, vol. 49, no. 1, pp. 16–27, 1983.

[49] R. D. Trumbower, M. A. Krutky, B.-S. Yang, and E. J. Perreault, "Use of self-selected postures to regulate multi-joint stiffness during unconstrained tasks," *PLoS One*, vol. 4, no. 5, 2009, Art. no. e5411.

[50] F. Mussa-Ivaldi, N. Hogan, and E. Bizzi, "Neural, mechanical, and geometric factors subserving arm posture in humans," *J. Neurosci.*, vol. 5, no. 10, pp. 2732–2743, 1985.

[51] E. J. Perreault, R. F. Kirsch, and P. E. Crago, "Voluntary control of static endpoint stiffness during force regulation tasks," *J. Neurophysiol.*, vol. 87, no. 6, pp. 2808–2816, 2002.

[52] D. W. Franklin, E. Burdet, R. Osu, M. Kawato, and T. E. Milner, "Functional significance of stiffness in adaptation of multijoint arm movements to stable and unstable dynamics," *Exp. Brain Res.*, vol. 151, no. 2, pp. 145–157, 2003.

[53] D. Shin, J. Kim, and Y. Koike, "A myokinetic arm model for estimating joint torque and stiffness from EMG signals during maintained posture," *J. Neurophysiol.*, vol. 101, no. 1, pp. 387–401, 2009.

[54] R. Osu and H. Gomi, "Multijoint muscle regulation mechanisms examined by measured human arm stiffness and EMG signals," *J. Neurophysiol.*, vol. 81, no. 4, pp. 1458–1468, 1999.

[55] A. Ajoudani, N. G. Tsagarakis, and A. Bicchi, "Tele-Impedance: Teleoperation with impedance regulation using a body-machine interface," *Int. J. Robot. Res.*, vol. 31, no. 13, pp. 1642–1655, 2012.

[56] J. Huang, X. Tu, and J. He, "Design and evaluation of the RUPERT wearable upper extremity exoskeleton robot for clinical and in-home therapies," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 46, no. 7, pp. 926–935, Jul. 2016.

[57] W. Wang *et al.*, "Toward patients' motion intention recognition: Dynamics modeling and identification of iLeg–An LLRR under motion constraints," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 46, no. 7, pp. 980–992, Jul. 2016.

[58] W. He, Y. Zhao, H. Tang, C. Sun, and W. Fu, "A wireless BCI and BMI system for wearable robots," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 46, no. 7, pp. 936–946, Jul. 2016.

[59] S. Bhattacharyya, S. Shimoda, and M. Hayashibe, "A synergetic brain-machine interfacing paradigm for multi-DOF robot control," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 46, no. 7, pp. 957–968, Jul. 2016.

[60] X. Zhao, Y. Chu, J. Han, and Z. Zhang, "SSVEP-based brain-computer interface controlled functional electrical stimulation system for upper extremity rehabilitation," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 46, no. 7, pp. 947–956, Jul. 2016.

[61] A. A. Saputra, J. Botzheim, I. A. Sulistijono, and N. Kubota, "Biologically inspired control system for 3-D locomotion of a humanoid biped robot," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 46, no. 7, pp. 898–911, Jul. 2016.

[62] Z. Yu *et al.*, "Gait planning of omnidirectional walk on inclined ground for biped robots," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 46, no. 7, pp. 888–897, Jul. 2016.

[63] S. Minaeian, J. Liu, and Y.-J. Son, "Vision-based target detection and localization via a team of cooperative UAV and UGVs," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 46, no. 7, pp. 1005–1016, Jul. 2016.

[64] R. Cui, Y. Li, and W. Yan, "Mutual information-based multi-AUV path planning for scalar field sampling using multidimensional RRT," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 46, no. 7, pp. 993–1004, Jul. 2016.

[65] F. Sun, C. Liu, W. Huang, and J. Zhang, "Object classification and grasp planning using visual and tactile sensing," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 46, no. 7, pp. 969–979, Jul. 2016.

[66] K.-C. Chan, C.-K. Koh, and C. S. G. Lee, "An automatic design of factors in a human-pose estimation system using neural networks," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 46, no. 7, pp. 875–887, Jul. 2016.

[67] Q. Ge, T. Shao, Q. Yang, X. Shen, and C. Wen, "Multisensor nonlinear fusion methods based on adaptive ensemble fifth-degree iterated cubature information filter for biomechatronics," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 46, no. 7, pp. 912–925, Jul. 2016.

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