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Active Exoskeleton Control Systems: State of the Art

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Abstract

To get a compliant active exoskeleton controller, the force interaction controllers are mostly used in form of either the impedance or admittance controllers. The impedance or admittance controllers can only work if they are followed by either the force or the position controller respectively. These combinations place the impedance or admittance controller as high-level controller while the force or position controller as low-level controller. From the application point of view, the exoskeleton controllers are equipped by task controllers that can be formed in several ways depend on the aims. This paper presents the review of the control systems in the existing active exoskeleton in the last decade. The exoskeleton control system can be categorized according to the model system, the physical parameters, the hierarchy and the usage. These considerations give different control schemes. The main consideration of exoskeleton control design is how to achieve the best control performances. However, stability and safety are other important issues that have to be considered.

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1. Introduction

The exoskeleton is an electromechanical structure worn by operator and matching the shape and functions of human body. It is able to augment the ability of human limb and/or to treat muscles, joints, or skeletal parts which are weak, ineffective or injured because of a disease or a neurological condition [1-3]. Moreover, it merges the machine power and the human intelligence in order to enhance the intelligence of the machine and to power the operator. The exoskeleton works mechanically in parallel with human body [1] and can be actuated passively and or actively.

The history of the active exoskeleton can be traced back to the 1960s. The US military had developed several exoskeletons to augment and amplify the soldier ability for military purposes [4]. Then, the General Electric Company developed two-armed master-slave manipulator used for handling radioactive equipment. The master is an exoskeleton type robot worn by the operator and its motion was reproduced by the two-arm slave unit [5]. Moreover, the John Hopkins University designed the upper limb exoskeleton type to help elbow flexion of paralyzed people [6]. Almost at the same time, the Beograd anthropomorphic exoskeleton was designed for lower limb application [7]. The development of the exoskeleton has been increased in various implementations.

The implementation of the exoskeleton can be classified into three main groups: human power augmentations, haptic interactions and rehabilitations. Firstly, the human power augmentations; Kanazawa Institute of Technology developed the full body exoskeleton for augmenting the nurse's power to take care of the patient [8]. In addition, University of Tsukuba has developed some generations of Robot Suit HAL (Hybrid Assistive Limb) to physically support a user's daily activities

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and heavy work [9]. The last is the BLEEX, a lower limb exoskeleton from Berkeley University. The BLEEX has been designed to augment the human limb so that the wearer is able to carry significant load easily over various terrains [10].

The second application of the exoskeleton is the haptic interactions. The first haptic exoskeleton is the Handyman and the Hardiman robot designed by GE Company in the early 1970s. It was a master-slave tele-operation system [5]. In the last decade, Gupta et al have developed the five DOF haptic arm exoskeleton for training and rehabilitation in virtual environment[11]. As Gupta et al, Carignan et al have developed an exoskeleton haptic interface for virtual task training. Then, Pierra et al have designed EXOSTATION, a complex haptic control station that allow the user to remotely control the virtual slave robot[12].

The rehabilitation is the last exoskeleton application. The rehabilitation exoskeletons have been developed for many purposes. They are implemented in either the lower limb for gait rehabilitation or the upper limb. The treadmill gait trainer is one implementation of gait rehabilitation. The LOKOMAT exoskeleton is an example of the early treadmill gait trainer[13, 14]. Moreover, there are many other treadmill exoskeletons besides LOKOMAT such as LOPES[15, 16], ALEX[17] and ANDROS[18]. In addition to treadmill gait trainer, the over-ground gait trainer has also been developed such as HAL [9] from University of Tsukuba, EXPOS from Sogang University[19], the lower limb exoskeleton from Shanghai Jiao Tong University[20], and Vanderbilt exoskeleton [21]. On other hand, the upper limb exoskeletons for rehabilitation have also been developed intensively, such as IntelliArm[22], SUEFUL-7[23], EXO-UL7[2], ARMin III[24], MGA [25, 26], L-Exos [27], RUPERT IV[28], BONES[29], WOTAS [30], UTS Exoskeleton[31, 32], and Pneu-Wrex[33].

So many exoskeletons existed today can be viewed from two aspects, mechanical and control system aspect. Mechanical characteristic of the exoskeleton has been reviewed many times. Gopura et al reviewed mechanical aspect of upper limb exoskeleton [34] [35], Bogue et al discussed the recent development of the exoskeleton [36], Diaz et al presented review of the lower limb exoskeleton for rehabilitation [37] as well as Yang et al [38] and others [39] [40]. However, the exoskeleton control system is rarely reviewed. Of the few is Jimenez-Fabian et al [41] who discussed the control system in the ankle exoskeleton and Lo[40] who gave small part view on the control system of upper limb exoskeleton. To fill the gap of knowledge in the exoskeleton control system, this paper presents the review of the control system architectures of the existing exoskeleton for last decade briefly.

2. The Exoskeleton control systems

2.1. Model-based Control systems

One of the exoskeleton control system categories is model-based control system. In general, according to the model used, the control strategy for the skeleton can be divided into two types: the dynamic model and the muscle model based control [40]. The dynamic exoskeleton model is derived through modeling the human body as rigid links joined together by joints (bones). This model is formed from combination of inertial, gravitational, coriolis and centrifugal effects[1, 40]. The dynamic model can be obtained through three ways; the mathematical model, the system identification and the artificial intelligent method.

The Mathematical model is obtained by modeling the exoskeleton theoretically based on physical characteristics of the system. The good example of this control system is the BLEEX, a 6-DOF lower limb exoskeleton[10]. In each leg, four DOF joints are hydraulically actuated while the rest are passive. The flexion-extension and abduction-adduction at the hip, flexion-extension on the knee and planar-dorsa flexion at the ankle are actuated while rotation and abduction-adduction at the ankle and rotation at the hip is passively actuated by using steel springs and elastomers[42]. The BLEEX only relied on its dynamic model to aid the user's movement, without any force/torque sensor to detect the interaction between the user and the exoskeleton[42, 43]. The control goal is to attain the system with high sensitivity. However, this sort of control aim demands the precise dynamic model. Three different dynamic models for the BLEEX have been developed and their variations are based on the walking cycle phases. They are the single support, the double support, and the double support with redundancy. Each dynamic model has different control mechanisms[44].

The second way to obtain the dynamic model is the system identification method. This method is used since it is difficult to attain a good dynamic model by using theoretical mathematic model. The BLEEX researchers have implemented the least square method for swing phase control[44]. The least square is utilized to estimate the parameter of the dynamic model based on the pairs of input-output data. Besides, Aguirre-Ollinger et al also employed the recursive least square method to estimate the dynamic model parameters of one DOF lower exoskeleton[45].

The last method for attaining the dynamic model is the artificial intelligent method. Its popularity to solve many non-linear problems has attracted some researchers to employ in in the dynamic model identification. Xiuxia et al used the wavelet neural network to identify the dynamic model of exoskeleton[46]. They implemented the wavelet neural network in the virtual joint torque control as inverse dynamic model. The inputs are the exoskeleton joint angular, the joint angle

human and the exoskeleton. The output of the impedance model is the force that becomes the reference force for the force/torque controller such that the force/torque of the exoskeleton is close or equal to the force reference. Another example is the low-level controller of the L-Exos, a 5 DOF exoskeleton with haptic interface. Other exoskeleton such as Pnuex-Wrex[58], WOTAS[30], Lokomat[13], LOPES[59] and AnDROS[18] applied torque/force controller as their low-level controller.

Besides the position and the torque/force, the interaction force between human and the exoskeleton are considered in the exoskeleton robot. The interaction force controller is applied as the high-level controller. The main goal is to provide proper help for the users in performing a task so that the force of human-exoskeleton interaction goes to zero. The interaction force can be controlled by either the impedance controller or the admittance controller. The basic concept of the impedance controller is it accepts position and produces force. While, the admittance is the opposite of the impedance controller; it accepts the force and yields the position[60].

The impedance controller is an extension of position control and it does not only control the position and the force but also control a relation and an interaction between the exoskeleton and the human body[60]. The impedance controller architecture contains the impedance model and the force/torque controller. The impedance model receives the error position of the joints and yields the force values that become the force references for the next stage, the force/torque controller. The force controller will try to guarantee the forces exerted by the exoskeleton are equal or close to the force references. ARMin III in Fig. 1 implemented the impedance controller. Others systems like SUEFUL-7[51], Pnue-Wrex[58], WOTAS[30], Lokomat[13], LOPES[59] and ANDROS[18] are also using same controller.

Besides the impedance control, the admittance control was utilized to control the force of human-robot interaction [61]. It contains the admittance model and the position control. The admittance model receives forces and produces positions, rather than receives positions and produces forces. The position controller will control the angle of exoskeleton joints based on the position references from the output of admittance model. Fig. 2 is an example of admittance controller for MGA upper limb exoskeleton[25]. Other instances are EXo-UL7[62] [63], iPAM[64], UTS[25], one DOF lower limb exoskeleton [65, 66].

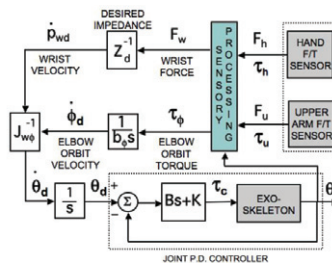


Fig. 2 The admittance controller for the MGA[25]

The impedance/admittance model represents the force of human-exoskeleton interaction. In most cases, the model parameters are fixed in the design. However, in some cases, these parameters need to change in order to adapt the high external changes such as the physical user condition. Therefore, the adaptive controller is required. Kiguchi et al utilized the neural-fuzzy networks to adapt internal parameter of impedance model[67].

2.4. Usage based Control systems

The exoskeleton control system can also be categorized according to the sort of applications such as the virtual reality controller, the tele-operation controller and the gait controller. Most upper limb exoskeletons have used the virtual reality controller in performing therapy exercises. This controller guides and helps the patient to carry on the tasks such as a virtual object reaching task in RUPERT [52], an object moving by virtual hand, a ball game, and a labyrinth game in ARmin [57], a virtual wall painting task in MGA[25], and a reaching and motion constrain task in L-Exos [68]. In those applications, the exoskeletons are considered as haptic devices.

The ball game therapy in Armin is an example of virtual reality controller, as seen in Fig.3. The patient has to catch the virtual ball rolling down to inclined virtual table. The virtual controller generates the reference trajectories and gives a proper help to the patients if they are off the track by sending error information to the high-level controller. This controller is complemented by the impedance controller as high-level controller and the gain force controller as low-level controller [69]. Improvement in trajectory generation was implemented in RUPERT III by using adaptive reference generator[70].

the next exoskeleton control system such as the assist as needed, the user's intention detection, the modularity, the safety and the stability. All these aspects have to be considered and incorporated in designing the control system for the exoskeleton to give better performance and better future implementation.

References

- [1]. Pons, J.L., 2008. *Wearable robots: biomechatronic exoskeletons*, Vol. 70. Wiley Online Library.
- [2]. Perry, J.C., J. Rosen, and S. Burns, 2007. Upper-Limb Powered Exoskeleton Design, *IEEE/ASME Transactions on Mechatronics*, vol. 12, no. 4, pp. 408-417.
- [3]. Low, K.H., 2011. "Robot-assisted gait rehabilitation: From exoskeletons to gait systems," Defense Science Research Conference and Expo (DSR).
- [4]. Cloud, W., 1965. Man amplifiers: Machines that let you carry a ton, *Popular Science*, vol. 187, no. 5, pp. 70-73&204.
- [5]. Mosher, R.S. and S.o.A. Engineers, 1967. *Handyman to hardiman*: Society of Automotive Engineers.
- [6]. SCHMEISSER, G. and W. SEAMONE, 1973. An upper limb prosthesis-orthosis power and control system with multi-level potential, *The Journal of Bone and Joint Surgery (American)*, vol. 55, no. 7, pp. 1493-1501.
- [7]. Vukobratovic, M., D. Hristic, and Z. Stojiljkovic, 1974. Development of active anthropomorphic exoskeletons, *Medical and Biological Engineering and Computing*, vol. 12, no. 1, pp. 66-80.
- [8]. Yamamoto, K., K. Hyodo, M. Ishii, and T. Matsuo, 2002. Development of power assisting suit for assisting nurse labor, *JSME International Journal Series C*, vol. 45, no. 3, pp. 703-711.
- [9]. Sankai, Y., 2011. *HAL: Hybrid Assistive Limb Based on Cybernetics Robotics Research*, M. Kaneko and Y. Nakamura, Editors., Springer Berlin / Heidelberg, p. 25-34.
- [10]. Zoss, A.B., H. Kazerooni, and A. Chu, 2006. Biomechanical design of the Berkeley lower extremity exoskeleton (BLEEX), *IEEE/ASME Transactions on Mechatronics*, vol. 11, no. 2, pp. 128-138.
- [11]. Gupta, A. and M.K. O'Malley, 2006. Design of a haptic arm exoskeleton for training and rehabilitation, *IEEE/ASME Transactions on Mechatronics*, vol. 11, no. 3, pp. 280-289.
- [12]. Letier, P., E. Motard, and J.P. Verschuere, 2010. "EXOSTATION : Haptic exoskeleton based control station," 2010 IEEE International Conference on Robotics and Automation (ICRA).
- [13]. Jezernik, S., G. Colombo, T. Keller, H. Frueh, and M. Morari, 2003. Robotic orthosis Lokomat: a rehabilitation and research tool, *Neurorehabilitation Technology at the Neural Interface*, vol. 6, no. 2, pp. 108-115.
- [14]. Riener, R., 2012. Technology of the Robotic Gait Orthosis Lokomat, *Neurorehabilitation Technology*, p. 221.
- [15]. Veneman, J.F., R. Kruidhof, E.E.G. Hekman, R. Ekkelenkamp, E.H.F. Van Asseldonk, and H. van der Kooij, 2007. Design and evaluation of the LOPES exoskeleton robot for interactive gait rehabilitation, *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 15, no. 3, pp. 379-386.
- [16]. van Asseldonk, E.H.F. and H. van der Kooij, 2012. Robot-Aided Gait Training with LOPES, *Neurorehabilitation Technology*, p. 379.
- [17]. Banala, S.K., S.H. Kim, S.K. Agrawal, and J.P. Scholz, 2009. Robot assisted gait training with active leg exoskeleton (ALEX), *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 17, no. 1, pp. 2-8.
- [18]. Unluharsicikli, O., M. Pietrusinski, B. Weinberg, P. Bonato, and C. Mavroidis, 2011. "Design and control of a robotic lower extremity exoskeleton for gait rehabilitation," 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).
- [19]. Kyoungchul, K. and J. Doyoung, 2006. Design and control of an exoskeleton for the elderly and patients, *IEEE/ASME Transactions on Mechatronics*, vol. 11, no. 4, pp. 428-432.
- [20]. Yin, Y., Y. Fan, and L. Xu, 2012. EMG & EPP-Integrated Human-machine Interface between the Paralyzed and Rehabilitation Exoskeleton, *IEEE Transactions on Information Technology in Biomedicine*, vol. PP, no. 99, pp. 1-1.
- [21]. Farris, R.J., H.A. Quintero, and M. Goldfarb, 2011. Preliminary Evaluation of a Powered Lower Limb Orthosis to Aid Walking in Paraplegic Individuals, *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 19, no. 6, pp. 652-659.
- [22]. Yupeng, R., P. Hyung-Soon, and Z. Li-Qun, 2009. "Developing a whole-arm exoskeleton robot with hand opening and closing mechanism for upper limb stroke rehabilitation," 2009 IEEE International Conference on Rehabilitation Robotics.
- [23]. Gopura, R.A.R.C., K. Kiguchi, and L. Yang, 2009. "SUEFUL-7: A 7DOF upper-limb exoskeleton robot with muscle-model-oriented EMG-based control," IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).
- [24]. Nef, T., M. Guidali, and R. Riener, 2009. ARMin III—arm therapy exoskeleton with an ergonomic shoulder actuation, *Applied Bionics and Biomechanics*, vol. 6, no. 2, pp. 127-142.
- [25]. Carignan, C., J. Tang, and S. Roderick, 2009. "Development of an exoskeleton haptic interface for virtual task training," IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).
- [26]. Liszka, M.S., 2006. *Mechanical design of a robot arm exoskeleton for shoulder rehabilitation*: ProQuest.
- [27]. Frisoli, A., M. Bergamasco, M.C. Carboncini, and B. Rossi, 2009. Robotic assisted rehabilitation in virtual reality with the L-EXOS, *Advanced Technologies in Rehabilitation*, vol. 145, pp. 40-54.
- [28]. Balasubramanian, S., W. Ruihua, M. Perez, B. Shepard, E. Koenenman, J. Koenenman, and H. Jiping, 2008. "RUPERT: An exoskeleton robot for assisting rehabilitation of arm functions," *Virtual Rehabilitation*.
- [29]. Klein, J., S.J. Spencer, J. Allington, K. Minakata, E.T. Wolbrecht, R. Smith, . . . D.J. Reinkensmeyer, 2008. "Biomimetic orthosis for the neurorehabilitation of the elbow and shoulder (BONES)," 2nd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob).
- [30]. Rocon, E., J.M. Belda-Lois, A.F. Ruiz, M. Manto, J.C. Moreno, and J.L. Pons, 2007. Design and Validation of a Rehabilitation Robotic Exoskeleton for Tremor Assessment and Suppression, *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 15, no. 3, pp. 367-378.
- [31]. Chetcuti, G., *Control Of A Robotic Upper Limb Exoskeleton For Use In Muscular Strength Augmentation And Rehabilitation*, 2011, University of Technology Sydney: Sydney. p. 92.
- [32]. UTS:NEWSROOM. *Robotics lab promises a new world for people with disabilities*. 2011 [cited 2012 23 March]; Available from: <http://newsroom.uts.edu.au/news/2011/11/robotics-lab-promises-a-new-world-for-people-with-disabilities>.
- [33]. Sanchez, R.J., Jr., E. Wolbrecht, R. Smith, J. Liu, S. Rao, S. Cramer, . . . D.J. Reinkensmeyer, 2005. "A pneumatic robot for re-training arm movement after stroke: rationale and mechanical design," 9th International Conference on Rehabilitation Robotics (ICORR).
- [34]. Gopura, R.A.R.C. and K. Kiguchi, 2009. "Mechanical designs of active upper-limb exoskeleton robots: State-of-the-art and design difficulties," IEEE International Conference on Rehabilitation Robotics (ICORR).

- [35]. Gopura, R.A.R.C., K. Kiguchi, and D.S.V. Bandara, 2011." A brief review on upper extremity robotic exoskeleton systems," 6th IEEE International Conference on Industrial and Information Systems (ICIS).
- [36]. Bogue, R., 2009. Exoskeletons and robotic prosthetics: a review of recent developments, *Industrial Robot: An International Journal*, vol. 36, no. 5, pp. 421-427.
- [37]. Diaz, I., J.J. Gil, and E. Sánchez, 2011. Lower-Limb Robotic Rehabilitation: Literature Review and Challenges.
- [38]. Yang, C.J., J.F. Zhang, Y. Chen, Y.M. Dong, and Y. Zhang, 2008. A review of exoskeleton-type systems and their key technologies, *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 222, no. 8, pp. 1599-1612.
- [39]. Dollar, A.M. and H. Herr, 2008. Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-Art, *IEEE Transactions on Robotics*, vol. 24, no. 1, pp. 144-158.
- [40]. Lo, H.S. and S.Q. Xie, 2011. Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects, *Medical Engineering & Physics*, no. 0.
- [41]. Jiménez-Fabián, R. and O. Verlinden, 2011. Review of control algorithms for robotic ankle systems in lower-limb orthoses, prostheses, and exoskeletons, *Medical Engineering & Physics*, no. 0.
- [42]. Kazerooni, H., J.L. Racine, H. Lihua, and R. Steger, 2005." On the Control of the Berkeley Lower Extremity Exoskeleton (BLEEX)," *Proceedings of the 2005 IEEE International Conference on Robotics and Automation (ICRA)*.
- [43]. Kazerooni, H., R. Steger, and L. Huang, 2006. Hybrid control of the berkeley lower extremity exoskeleton (bleex), *The International Journal of Robotics Research*, vol. 25, no. 5-6, pp. 561-573.
- [44]. Ghan, J., R. Steger, and H. Kazerooni, 2006. Control and system identification for the Berkeley lower extremity exoskeleton (BLEEX), *Advanced Robotics*, vol. 20, no. 9, pp. 989-1014.
- [45]. Aguirre-Ollinger, G., J.E. Colgate, M.A. Peshkin, and A. Goswami, 2007." Active-Impedance Control of a Lower-Limb Assistive Exoskeleton," *IEEE 10th International Conference on Rehabilitation Robotics (ICORR)*.
- [46]. Xiuxia, Y., L. Gui, Y. Zhiyong, and G. Wenjin, 2008." Lower Extreme Carrying Exoskeleton Robot Adaptive Control Using Wavelet Neural Networks," *Fourth International Conference on Natural Computation (ICNC)*.
- [47]. Rosen, J., M.B. Fuchs, and M. Arcan, 1999. Performances of Hill-Type and Neural Network Muscle Models--Toward a Myosignal-Based Exoskeleton, *Computers and Biomedical Research*, vol. 32, no. 5, pp. 415-439.
- [48]. Rosen, J., M. Brand, M.B. Fuchs, and M. Arcan, 2001. A myosignal-based powered exoskeleton system, *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans*, vol. 31, no. 3, pp. 210-222.
- [49]. Cavallaro, E.E., J. Rosen, J.C. Perry, and S. Burns, 2006. Real-Time Myoprocessors for a Neural Controlled Powered Exoskeleton Arm, *IEEE Transactions on Biomedical Engineering*, vol. 53, no. 11, pp. 2387-2396.
- [50]. Hashemi, J., E. Morin, P. Mousavi, K. Mountjoy, and K. Hashtrudi-Zaad, 2011. EMG-force modeling using parallel cascade identification, *Journal of Electromyography and Kinesiology*, no. 0.
- [51]. Kiguchi, K. and Y. Hayashi, 2012. An EMG-Based Control for an Upper-Limb Power-Assist Exoskeleton Robot, *IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics*, vol. PP, no. 99, pp. 1-8.
- [52]. Hang, Z., S. Balasubramanian, W. Ruihua, H. Austin, S. Buchanan, R. Herman, and H. Jiping, 2010." RUPERT closed loop control design," 2010 Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC).
- [53]. Suzuki, K., G. Mito, H. Kawamoto, Y. Hasegawa, and Y. Sankai, 2007. Intention-based walking support for paraplegia patients with Robot Suit HAL, *Advanced Robotics*, vol. 21, no. 12, pp. 1441-1469.
- [54]. Frisoli, A., E. Sotgiu, C. Procopio, M. Bergamasco, B. Rossi, and C. Chisari, 2011." Design and implementation of a training strategy in chronic stroke with an arm robotic exoskeleton," 2011 IEEE International Conference on Rehabilitation Robotics (ICORR).
- [55]. Gomes, M., G. Silveira, and A. Siqueira, 2011. Gait Pattern Adaptation for an Active Lower-Limb Orthosis Based on Neural Networks, *Advanced Robotics*, vol. 25, no. 15, pp. 1903-1925.
- [56]. Tsai, B.C., W.W. Wang, L.C. Hsu, L.C. Fu, and J.S. Lai, 2010." An articulated rehabilitation robot for upper limb physiotherapy and training," 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).
- [57]. Nef, T., M. Mihelj, G. Kiefer, C. Perndl, R. Muller, and R. Riener, 2007." ARMin - Exoskeleton for Arm Therapy in Stroke Patients," *IEEE 10th International Conference on Rehabilitation Robotics (ICORR)*.
- [58]. Wolbrecht, E.T., D.J. Reinkensmeyer, and J.E. Bobrow, 2010. Pneumatic control of robots for rehabilitation, *The International Journal of Robotics Research*, vol. 29, no. 1, pp. 23-38.
- [59]. Tsukahara, A., Y. Hasegawa, and Y. Sankai, 2011." Gait support for complete spinal cord injury patient by synchronized leg-swing with HAL," 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).
- [60]. Hogan, N., 1985. Impedance Control: An Approach to Manipulation: Part I---Theory, *Journal of dynamic systems, measurement, and control*, vol. 107, no. 1, pp. 1-7.
- [61]. Carignan, C.R., S.N. Roderick, and M.P. Naylor, 2007." Distributed control and safety system for a rehabilitation arm exoskeleton," *ASME*.
- [62]. Miller, L.M. and J. Rosen, 2010." Comparison of multi-sensor admittance control in joint space and task space for a seven degree of freedom upper limb exoskeleton," 3rd IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechanics (BioRob).
- [63]. Wen, Y., J. Rosen, and L. Xiaou, 2011." PID admittance control for an upper limb exoskeleton," *American Control Conference (ACC)*.
- [64]. Culmer, P.R., A.E. Jackson, S. Makower, R. Richardson, J.A. Cozens, M.C. Levesley, and B.B. Bhakta, 2010. A Control Strategy for Upper Limb Robotic Rehabilitation With a Dual Robot System, *Mechatronics, IEEE/ASME Transactions on*, vol. 15, no. 4, pp. 575-585.
- [65]. Aguirre-Ollinger, G., J.E. Colgate, M.A. Peshkin, and A. Goswami, 2011. Design of an active one-degree-of-freedom lower-limb exoskeleton with inertia compensation, *The International Journal of Robotics Research*, vol. 30, no. 4, pp. 486-499.
- [66]. Aguirre-Ollinger, G., J.E. Colgate, M.A. Peshkin, and A. Goswami, 2012. Inertia Compensation Control of a One-Degree-of-Freedom Exoskeleton for Lower-Limb Assistance: Initial Experiments, *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 20, no. 1, pp. 68-77.
- [67]. Kiguchi, K., T. Tanaka, and T. Fukuda, 2004. Neuro-fuzzy control of a robotic exoskeleton with EMG signals, *IEEE Transactions on Fuzzy Systems*, vol. 12, no. 4, pp. 481-490.
- [68]. Frisoli, A., L. Borelli, A. Montagner, S. Marcheschi, C. Procopio, F. Salsedo, . . . B. Rossi, 2007." Arm rehabilitation with a robotic exoskeleton in Virtual Reality," *IEEE 10th International Conference on Rehabilitation Robotics (ICORR)*.
- [69]. Nef, T., M. Mihelj, and R. Riener, 2007. ARMin: a robot for patient-cooperative arm therapy, *Medical & Biological Engineering & Computing*, vol. 45, no. 9, pp. 887-900.
- [70]. Balasubramanian, S. and J. He, 2012. Adaptive control of a wearable exoskeleton for upper-extremity neurorehabilitation, *Applied Bionics and Biomechanics*, vol. 9, no. 1, pp. 99-115.
- [71]. Schiele, A. and G. Visentin, 2003." The ESA human arm exoskeleton for space robotics telepresence."