

# Antagonistic Mono- and Bi-Articular Lower-Limb Muscle Activities' Model Characterization at Different Speeds

*M.A.M Dzahir*<sup>1,\*</sup>, *N.S.M Nor*<sup>1</sup>, *A. Azaman*<sup>2</sup>, *M. Hussein*<sup>1</sup>, and *M.A. Mat Dzahir*<sup>1</sup>

<sup>1</sup>Department of Applied Mechanics & Design, Faculty of Mechanical Engineering, UTM, Malaysia

<sup>2</sup>Department of Biotechnology & Medical Engineering, Faculty of Biomedical Engineering and Health Science, UTM, Malaysia

**Abstract.** Nowadays, medical rehabilitation system has become a requirement due to increment in national rehabilitation centres and medical hospitals. An assistive rehabilitation orthosis becomes essential and was used for rehabilitation therapy, condition monitoring, and physical strengthening. This study focused on the lower limb assistive rehabilitation orthosis development using pneumatic artificial muscle. To successfully control this orthosis system which consists of antagonistic mono- and bi-articular muscle actuators, it is necessary to construct a reliable control algorithm. The suitable control scheme and strategy to manoeuvre this orthosis system similar to human musculoskeletal system have yet to be fully developed and established. Based on the review study, it is said that the co-contraction controls of anterior-posterior pneumatic muscles was able to improve the joint stiffness and stability of the orthosis as well as good manoeuvrability. Therefore, a characterization model of an antagonistic mono- and bi-articular muscles activities of human's lower-limb during walking motion will be necessary. A healthy young male subject was used as test subject to obtain the sEMG muscle activities for antagonistic mono- and bi-articular muscles (i.e., Vastus Medialis-VM, Vastus Lateralis-VL, Rectus Femoris-RF, and Bicep Femoris-BF). The tests were carried out at different speeds of 2km/h, 3km/h, and 4km/h for one minute walking motion on a treadmill. Then, the patterns of the sEMG muscle activities were modelled and characterised using fifth order polynomial equation. Based on the results, it is shown that the anterior and posterior muscles were exhibited a muscle synergy in-between multiple anterior or posterior muscles and muscle co-contraction between anterior-posterior muscles in order to control the movements at the joints during walking motion. As conclusion, it is proven that the sEMG muscle activities of the antagonistic mono- and bi-articular muscles were follow a certain contraction-expansion patterns during walking motion even when it were tested at different gait cycle speeds.

---

\* Corresponding author: [azuwan@mail.fkm.utm.my](mailto:azuwan@mail.fkm.utm.my) / [azuwan@fkm.utm.m](mailto:azuwan@fkm.utm.m)

## 1 Introduction

Based on the development of different orthosis systems in the last ten years, it can be concluded that the researchers' interest had been shifted into the implementation of the natural type of compliant actuators [1–10]. Although lots of researches have been investigated regarding the co-contraction movements of human antagonistic muscles. Their model implementations in controlling the antagonistic mono- and bi-articular muscle actuators of lower-limb orthosis have not been completely discovered [11–22]. In addition, research study which focuses on the implementations of mono- and bi-articular actuators using pneumatic muscles for the lower-limb rehabilitation orthosis also have yet to be extensively investigated [23–25]; thus, simply actuate the muscle actuators might not give a good result on the joint's stiffness and stability of the lower-limb leg orthosis and its joint trajectories. Therefore, based on the related research findings, the simultaneous co-contractively like movements between the anterior and posterior actuators could be considered within the control scheme and strategy [26–30]. Even though a considerable amount of works has been done, the field is still rapidly evolving. The issues on which are the most effective control algorithm is still wide open. However, the randomized controlled trials are still necessary for identifying the suitable control algorithms even though it is expensive and time-consuming.

Throughout the review articles, it can be hypothesis that the human antagonistic mono- and bi-articular muscles are simultaneously activated in-between anterior-posterior muscles. In other words, when the anterior muscle is contracts, the posterior muscle will be expand and vice versa. This is defined as a muscle co-contraction in-between antagonistic muscles (i.e., anterior and posterior) which is also could be explained as contraction-expansion movements between anterior and posterior muscles [23–25]. The muscle co-contraction refers to when any movement occurs which involved two sets of muscles working around a specific joint. Normally, it is required that the muscles on one side of the joint must be relaxed, so that the other muscles on the other side can be contract. The definition of the co-contraction also could be referred to both muscles were simultaneously contract [23, 25]. When the muscles on one side of the joint are in contraction, the opposite muscles will not be in completely relaxed state. There are still some contraction involves but it is less than the opposite muscles. In addition, there might be some existing delay occurs as well during the activation of the anterior and posterior muscles. Furthermore, the same side of anterior or posterior muscles should follow the same contraction-expansion patterns which is define as a muscle synergy. The muscle synergy of the same side either anterior or posterior muscles refers to the interaction of two or more sets of muscles to produce a combined effect greater than the summation of their separate effects.

The result of this research study will verify the isotonic muscle co-contraction patterns of the human lower limb muscles on both the antagonistic mono- and bi-articular muscles. Thus, in this paper a model characterization of the antagonistic mono- and bi-articular muscles of human's lower-limb during walking motion on treadmill system is proposed. The purpose of this study is to determine the characteristics and behaviours of the antagonistic mono- and bi-articular muscles contraction-expansion patterns when tested at different gait cycle speeds using a surface electromyography (sEMG). Through this, we are able to determine and verified the characteristics of the antagonistic mono- and bi-articular muscles' contraction-expansion patterns, whether it were followed a certain pattern or not when tested at different walking speeds. However, it is difficult to measure all of the lower-limb muscle activities using sEMG electrodes due to weak muscle activities, small muscle sites, and difficult location to place the electrodes. Therefore, only four muscles (i.e., VM, VL, RF, and BF muscles) were chosen to record the required muscle activities data.

## 2 Methodology

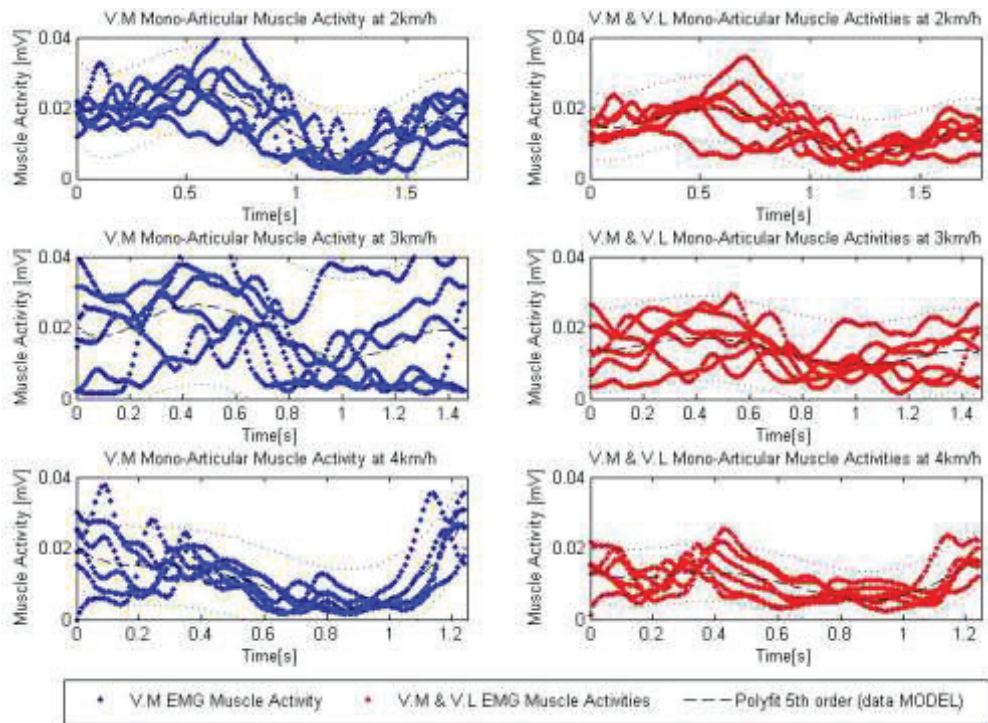
In this research, a healthy and young male subject aged 29 years old with weight 68kg and height 174cm is used as a test subject. The subject is an active tennis player and has a strong lower limb muscles due to flexible movements in multiple directions (i.e., forward, backward, side step, jumping etc.). For this preliminary study, four muscles are selected to represent the anterior-posterior mono- and bi-articular muscles. The mono-articular muscles are Vastus Medialis (VM) and Vastus Lateralis (VL). These muscles are used to verify the muscle synergy between multiple anterior muscles. Meanwhile, the bi-articular muscles are Rectus Femoris (RF) and Bicep Femoris (BF). These muscles are used to verify the muscle co-contraction between anterior and posterior muscles. Four sEMG electrodes (TMSi system, Netherland) are placed at VM, VL, RF and BF muscles location to obtain sEMG muscle activities of the selected muscles. The tests are carried out at some different speeds of 2km/h, 3km/h, and 4.0 km/h during walking motion on a treadmill. For each VM, VL, RF and BF muscles, the data was collected for duration of about one minute on a treadmill and minimum of fourteen complete cycles of walking motion were successfully recorded. The data were then processed, filtered, and rectified to remove all of the unnecessary noise using Microsoft Excel and MATLAB software. Then the scattered data of the muscle activities are obtained for one complete cycle of walking motion at different walking speeds. Finally, the fitting method using fifth order polynomial equation is used to characterise the patterns for the antagonistic mono- and bi-articular sEMG muscle activities. The characteristic of the antagonistic mono- and bi-articular muscles will be useful for the development of a control scheme and strategy of the pneumatic muscle actuated lower limb orthosis.

## 3 Results and discussion

The purpose of this research study is to determine the characteristics and behaviours of the antagonistic mono- and bi-articular muscles of lower limb during walking motion. It is strongly believed that each single mono- and bi-articular muscle have a specific isotonic contraction-expansion pattern which can be verified and modelled. The verified models of each anterior and posterior muscle will be useful for controlling the pneumatic muscle actuated lower limb orthosis. This is because, the pneumatic artificial muscle requires pressure as the input and a contraction value will be used to determine the amount of pressure input for manipulating the joint movements accurately. However, the hysteresis effects of the pneumatic artificial muscle during contraction-expansion should also be considered into the control scheme.

Figure 1 shows the VM muscle activities and combined VM-VL sEMG muscle activities at different gait cycle speeds of 2km/h, 3km/h and 4km/h. The VM and VL muscles were both an anterior mono-articular muscles which manipulate the knee joint movements. A fifth order polynomial fitting equation was used to represent a model for the contraction-expansion patterns of VM muscle and combination of VM-VL muscles at different walking speeds. Based on the interpretation of the results, it shows that the contraction-expansion of VM muscle gave an almost similar pattern at all gait cycle speeds. These prove that, each one single muscle will follow a certain contraction-expansion pattern and it was not affected by an implementation of different gait cycle speeds. This result can be verified with a derivation model of simplified pneumatic muscle actuated lower limb orthosis. In addition, the combination of VM-VL muscles was tested to prove that same anterior or posterior muscles could have a similar contraction-expansion pattern, and the combination of both muscles would produce a muscle synergy and improving the

movement at the specific joint. To perform the analysis, both VM and VL muscles were combined and then its average values were determined. Based on the results at different gait cycle speeds, an improvement was spotted within the contraction-expansion patterns of combined VM-VL muscles. The obtained patterns show a much better result in terms of consistencies of the muscle activities. In addition, even though the fifth order polynomial fitting equation model of the VM muscle (black lines – first column) shows almost the same patterns, however its contraction-expansion patterns (blue lines) were not consistent enough at different gait cycle speeds. On the contrary, the fifth order polynomial fitting equation model of the combined VM-VL muscles (black lines – second column) were very consistent and it shows an exactly the same patterns even when tested at different gait cycle speeds.

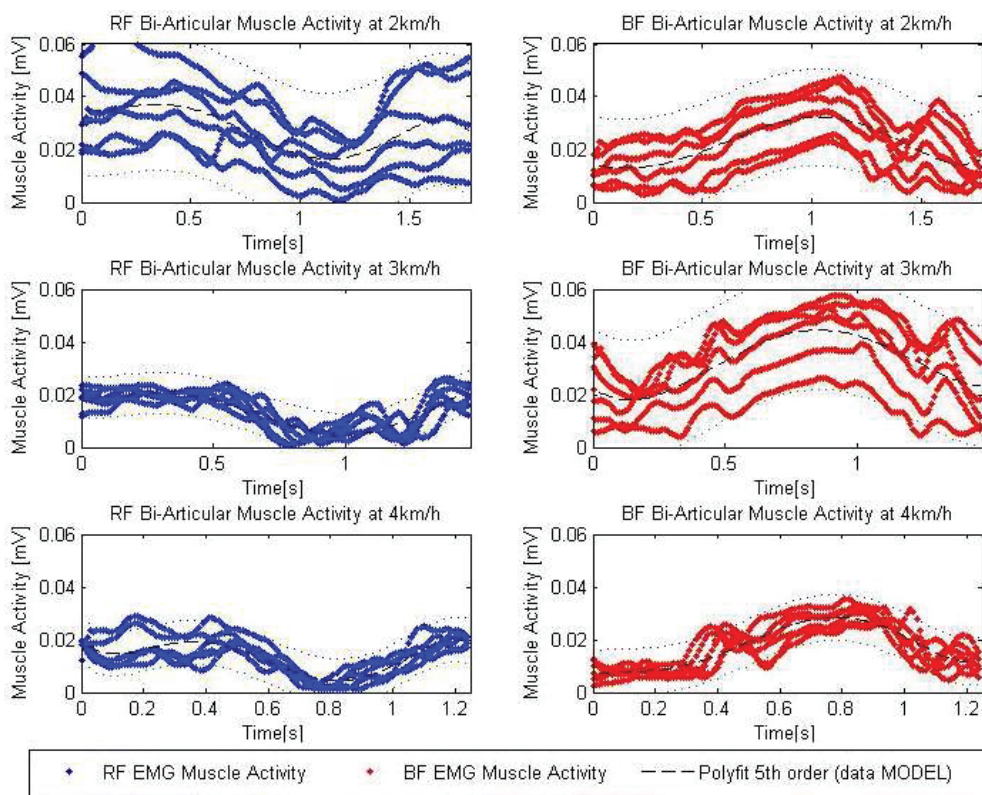


**Fig. 1.** Vastus Medialis (VM) and Vastus Lateralis (VL) sEMG muscle activities and its 5th order polynomial fitting equations at different walking speeds of 2, 3 and 4km/h.

Figure 2 shows the RF and BF sEMG muscle activities at different gait cycle speeds of 2km/h, 3km/h and 4km/h. The RF muscle is an anterior bi-articular muscle while the BF muscle is a posterior bi-articular muscle. These two muscles provide assistance to the mono-articular muscles in order to improvise and strengthen the movements at hip and knee joints. A fifth order polynomial fitting equation was used to model a contraction-expansion pattern of the RF and BF muscles at different walking speeds. Based on the evaluation of the results, it shows that the contraction-expansion of RF and BF muscle also gave an almost similar pattern when tested at different gait cycle speeds. These were very similar to the results shown by the VM and VM-VL sEMG muscle activities contraction-expansion patterns, where one single muscle will follow a certain contraction-expansion pattern during one complete cycle of walking motion. However, compared to the muscle synergy



that was produced by the VM-VL muscles (both were anterior muscles), the RF and BF muscles were not able to generate a muscle synergy between them because they were made of different anterior and posterior muscles. Instead of the muscle synergy, the muscle co-contraction was found in-between the anterior and posterior muscles. According to the result analysis, the RF and BF muscles exhibit co-contraction movements between them, where the contraction-expansion pattern of the anterior muscle was completely opposite to the posterior muscle. This was verified at different gait cycle speeds. However, there was an existing delay in between the activation of the anterior and posterior muscles which is approximately 35% of the walking motion depending on the gait cycle speeds. Furthermore, the contraction-expansion patterns of both RF and BF muscles become more consistent as the walking speed increased. This shows that, muscle reaction between anterior and posterior muscles becomes more active and reacts much faster to provide assistance to the joint's movements. As a final point, existing delay between the activation of the anterior and posterior muscles could also be reduced with the incremental of the walking speed.



**Fig. 2.** Rectus Femoris (RF) and Bicep Femoris (BF) sEMG muscle activities and its 5th order polynomial fitting equations at different walking speeds of 2, 3 and 4km/h

### 4 Conclusions

As conclusions, the objectives of the research study have been fulfilled. According to the results, the sEMG muscle activities of the antagonistic mono- and bi-articular lower limb

muscles follow a certain contraction-expansion patterns during walking motion even when it were tested at different gait cycle speeds. These patterns were defined as muscle synergy and muscle co-contraction. First is the muscle synergy, where multiple anterior or posterior muscles with same contraction-expansion pattern were combined together to produce more accurate movement at the joints. Based on the results, it shows that the fifth order contraction-expansion model of combined VM and VL sEMG muscle activities displayed an exactly similar pattern at different gait cycle speeds of 2km/h, 3km/h and 4km/h. These results conclude that each one of the anterior-posterior mono- and bi-articular muscles has a certain pattern to be followed during walking motion which was not affected by implementation of different gait cycle speeds. Secondly, muscle co-contraction where a set of anterior and posterior mono- or bi-articular muscles have a contraction-expansion patterns which were completely opposite to each other's. In addition, muscle co-contraction has an existing delay of approximately 35% of its corresponding gait cycle time. The contraction-expansion patterns of both RF and BF sEMG muscle activities become more consistent as the walking speed increased. This result demonstrates that the muscles reaction between anterior and posterior muscles becomes more active and able to react much faster in order to provide assistance to the joint's movements. With these results, it would be a huge benefit if the models could be verified with the simplified model of the pneumatic muscle actuated lower limb orthosis, and determine its significant value. Then, implementing the obtained models into the control scheme and strategy of the pneumatic muscle actuated lower limb orthosis.

## Acknowledgements

This research study was supported by Potential Academic Staff (PAS) research grants Q.J130000.2724.02K16, Universiti Teknologi Malaysia (UTM).

## References

1. B.G. Nascimento, C.B. Vimieiro, D.A. Nagem, M. Pinotti, "Hip orthosis powered by pneumatic artificial muscle: Voluntary activation in absence of myoelectrical signal", *Artif. Organs*, **32**, 317–322 (2008)
2. C.B.S. Vimieiro, B.G. Nascimento, D.A.P Nagem, M. Pinotti, "Development of a hip orthosis using pneumatic artificial muscles", In *Proceeding of TMSi*, (2005) July18–1; São Paulo, Spain
3. K. Bharadwaj, T.G. Sugar, "Kinematics of a robotic gait trainer for stroke rehabilitation", In *Proceedings of the IEEE International Conference on Robotics and Automation*, (2006) May 15–19; Orlando, FL, USA
4. D.P. Ferris, K.E. Gordon, G.S. Sawicki, A. Peethambaran, "An improved powered ankle-foot orthosis using proportional myoelectric control", *Gait Posture* **23**, 425–428 (2006)
5. D.P. Ferris, J.M. Czerniecki, B. Hannaford, "An ankle-foot orthosis powered by artificial pneumatic muscles", *J. Appl. Biomechanics*, **21**, 189–197 (2005)
6. K.E. Gordon, G.S. Sawicki, D.P. Fessis, "Mechanical performance of artificial pneumatic muscles to power an ankle-foot orthosis", *J. Biomech.*, **39**, 1832–1841 (2006)
7. N. Costa, M. Bezdicek, M. Brown, J.O. Gray, D.G. Caldwell, "Joint motion control of a powered lower limb orthosis for rehabilitation", *Int. J. Autom. Computation*, **3**, 271–281 (2006)

8. T. Miyoshi, K. Hiramatsu, S.I. Yamamoto, K. Nakazawa, M. Akai, "Robotic gait trainer in water: Development of an underwater gait-training orthosis", *Disabil. Rehabilitation*, **30**, 81–87 (2008)
9. P. Malcom, P. Fiers, V. Segers, I. Caekenberghe, M. Lenoir, D. Clercq, "Experimental study on the role of the ankle push off in the walk-to-run transition by means of a powered ankle-foot-exoskeleton", *Gait Posture*, **30**, 322–327 (2009)
10. P. Malcom, V. Segers, I. Caekenberghe, D. Clercq, "Experimental study of the influence of the m. tibialis anterior on the walk-to-run transition by means of a powered ankle-foot-exoskeleton", *Gait Posture*, **29**, 6–10 (2009)
11. S. Galle, P. Malcom, W. Derave, D. Clercq, "Adaptation to walking with an exoskeleton that assists ankle extension", *Gait Posture*, **38**, 495–499 (2013)
12. P. Malcom, W. Derave, S. Galle, D. Clercq, "A simple exoskeleton that assist plantarflexion can reduce the metabolic cost of human walking", *PLoS One*, **8**, 0056137 (2013)
13. G.S. Sawicki, D.P. Fessis, "A pneumatically powered knee-ankle-foot orthosis (KAFO) with myoelectric activation and inhibition", *J. Neuro-Eng. Rehabil.*, **6**, 23:1–23:16 (2009)
14. T.T. Deaconescu, A.I. Deaconescu, "Pneumatic muscle actuated equipment for continuous passive motion", *IAENG Trans. Eng. Technol.*, doi:10.1063/1.3256258 (2009)
15. B. Pieter , V.D. Michael, V.H. Ronald, V. Bram, L. Dirk, "Design and control of lower limb exoskeleton for robot-assisted gait training", *Applied Bionics and Biomechanics*, **6**(2), 229–243 (2009)
16. B. Pieter , V.D. Michael, V.H. Ronald, V. Bram, L. Dirk, "Pleated pneumatic artificial muscle based actuator system as a torque source for compliant lower limb exoskeletons", *IEEE/ASME Transactions on Mechatronics*, **19**(3), 1046–1056 (2014)
17. T.J. Yeh, M.J. Wu, T.J. Lu, F.K. Wu, C.R. Huang, "Control of McKibben pneumatic muscles for a power-assist, lower-limb orthosis", *Mechatronics*, **20**, 686–697 (2010)
18. J. Carberry, G. Hinchly, J. Buckerfield, E. Taylor, T. Burton, S. Madgwick, R. Vaidyanathan, "Parametric design of an active ankle foot orthosis with passive compliance", In *Proceedings of the Computer-Based Medical System (CBMS)*, (2011) June 27–30; Bristol, UK
19. Y. Park, B. Chen, D. Young, L. Stirling, R. Wood, E. Goldfield, R. Nagpal, "Bio-inspired Active Soft Orthotic Device for Ankle Foot Pathologies", In *Proceedings of the International Conference on Robots and Systems (IROS)*, (2011) September 25–30; San Francisco, CA, USA
20. Y. Park, B. Chen, C. Majidi, R. Wood, R. Nagpal, E. Goldfield, "Active Modular Elastomer Sleeve for Soft Wearable Assistance Robots", In *Proceedings of the IEEE International Conference on Robots and Systems (IROS)*, (2012) October 7–12; Vilamoura, Portugal
21. C.M. Teng, Z.Y. Wong, W.Y. The, Y.Z. Chong, "Design and development of inexpensive pneumatically-powered assisted knee-ankle-foot orthosis for gait rehabilitation-preliminary finding", In *Proceedings of the International Conference on Biomedical Engineering (ICoBE)*, (2012) February 27–28; Penang, Malaysia
22. T. Kawamura, K. Takanaka, "Development of an orthosis for walking assistance using pneumatic artificial muscle-a quantitative assessment of the effect of assistance", In *Proceedings of the International Conference on Rehabilitation Robotics*, (2013) June 24–26; Seattle, WA, USA
23. M.A.M. Dzahir, S.I. Yamamoto, "Design and Evaluation of the AIRGAIT Exoskeleton: Leg Orthosis Control for Assistive Gait Rehabilitation", *Journal of Robotics*, vol. **2013**, Article ID 535106, 20 pages, doi:10.1155/2013/535106 (2013)

24. P. Flavio, M.A.M. Dzahir, S.I. Yamamoto, “Computed-torque method for the control of a 2 DOF orthosis actuated through pneumatic artificial muscles: a specific case for the rehabilitation of the lower limb”, *Medical Physics*, arXiv: 1404.6968 [physics.med-ph] (2014)
25. M.A.M. Dzahir, S.I. Yamamoto, “Recent trends in lower-limb robotic rehabilitation orthosis: control scheme and strategy for pneumatic muscle actuated gait trainers”, *Robotics*, **3**(2), 120–148 (2014)
26. S. Hussain, S.Q. Xie, P.K. Jamwal, “Adaptive impedance control of a robotic orthosis for gait rehabilitation”, *IEEE Trans. Cybern.*, **43**, 1025–1034 (2013)
27. S. Hussain, S.Q. Xie, P.K. Jamwal, “Robust nonlinear control of an intrinsically compliant robotic gait training orthosis”, *IEEE Trans. Syst. Man Cybern.: System*, **43**, 655–665 (2013)
28. K.D. William, “Task-based methods for evaluating electrically stimulated antagonist muscle controllers”, *IEEE Trans. on Biomedical Engineering*, **36** (1989)
29. M. Samer, F. Philippe, G. David, P. Philippe, E.M. Hassan, “Towards a co-contraction muscle control strategy for paraplegics”. *IEEE Conf. on Decision and Control*. (2005).
30. H. Stewart, F. Norm, B. Michael, “Muscle co-contraction modulates damping and joint stability in a three-link biomechanical limb”, *Frontiers in Neurorobotics*, **5** (2012)