Low Cost Lower Limb Exoskeleton for Assisting Gait Rehabilitation: Design and Evaluation

Luis I. Minchala[1], Anthony J. Velasco[2], Jonathan M. Blandin[3], Fabian Astudillo-Salinas[4], Andres Vazquez-Rodas[5]
Universidad de Cuenca
Cuenca, Ecuador
[1]ismael.minchala@ucuenca.edu.ec, [2]anthony.velasco@ucuenca.edu.ec,
[3]jonathan.blandin@ucuenca.edu.ec, [4]fabian.astudillos@ucuenca.edu.ec,
[5]andres.vazquezr@ucuenca.edu.ec

ABSTRACT

This paper presents the design and implementation of a low cost, yet robust, three degrees of freedom (DoF) lower limb exoskeleton intended to assist patients in gait rehabilitation. The majority of patients with incomplete spinal cord injuries (SCI) are able to walk after a rehabilitation process. Among the broad options of physical rehabilitation therapies, there is a relatively recent interest in those assisted by robotic exoskeletons, due to features as high precision movements and automated repetitions. In this context, the subsystems of the exoskeleton prototype described throughout this paper are the following: i) a controlled area network (CAN) communications bus with SDO protocol; and, ii) a hierarchical control system consisting of two levels: a trajectory generator of the walk biomechanics implemented in a centralized controller (CC), and distributed controllers (DC) installed at each joint of the exoskeleton. The multiplication mechanical system uses reduction speed boxes based on cycloidal and planetary gears. Experimental results of the prototype operating, with and without carrying weight, show effectiveness of the whole control system for tracking a non-pathological gait biomechanics trajectory.

CCS Concepts

• General and reference → General conference proceedings.

Keywords

CAN, control, lower limb, exoskeleton, instrumentation system

1. INTRODUCTION

Currently, robotic technology applications spread in a broad number of fields, among which is physical rehabilitation. Physical impairments in lower limbs are the most common disabilities, since the majority of the body weight is supported by the lower limbs, which are responsible of the body displacement, even under extreme circumstances such as climbing [1].

Robotic exoskeletons are able to assist limb movements as well as to provide missing capabilities of the human body, so their applications are easily adapted to physical rehabilitation, whose primary outcome is the patient's ability to recover walking independence [2]. The interaction between these devices and users is mainly performed by digital systems which process biometric signals to anticipate movement intentions [3] and to coordinate the device motion with the user movements [4], enabling autonomous operation of the exoskeletons while used by patients [5].

There is a variety of research works focused in the design and implementation of exoskeletons to assist patients who suffered from SCI. For instance, [6] presents an exoskeleton prototype with bi-articular actuation in the ankle, strength measurement in the soles of the feet for characterizing the gait cycle, and compliant control. The authors of [7] propose an adaptive control strategy applied to a knee active orthosis, which reduces energy demand under perturbation scenarios. In [8] is proposed a four DoF exoskeleton for the right lower limb with an adaptive control system. Reference [9] details the design features of a lower limb exoskeleton focused in the assistance of elderly people for stairs climbing.

A common disadvantage of the research previously cited is the scarce detail reported about the implementation of the control and communications systems of the prototypes, omitting, for example, important information about the structure of the communication frames as well as the protocol operation in the link and application layers. Additionally, there is minimum facts about the difficulties encountered throughout the implementation process of the prototypes, and their limitations.

This paper presents the design and implementation of the communications and control systems of a three DoF lower limb exoskeleton. The proposed control system uses a hierarchical architecture in which a centralized controller is in charge of generating accurate information of the gait biomechanics (set-points) to be transmitted to the DCs, which execute the actuators movements. The payload of the exoskeleton is managed by a CAN bus to which, every DC is attached in a master-salve architecture. Experimental results show effectiveness in the whole operation of the prototype.

ICACR 2019, October 11–13, 2019, Prague, Czech Republic

ACM ISBN 978-1-4503-7288-6/19/10…$15.00
DOI: https://doi.org/10.1145/3365265.3365276

Table 1: Main features of the actuators installed in the ALLEX prototype

Feature	Hip joint	Knee/Ankle joint
Model	Maxon:EC90	Maxon:EC45
Output power (W)	90	70
Nominal torque (mNm)	444	128
Nominal current (A)	6.06	3.21
Nominal speed (rpm)	2590	4860

2. EXOSKELETON PROTOTYPE

The proposed prototype intends to have as key feature autonomous operation for gait rehabilitation in patients with incomplete SCI. In this context, the short name for the prototype hereafter is ALLEX, which stands for autonomous lower limb exoskeleton. The current version of ALLEX (v1.0) has three DoF aligned in the sagittal plane, one per each articulation in the left leg: hip, knee, and ankle. This prototype is classified within the active orthosis for gait assistance. Fig. 1 shows the angular biomechanics of the articulations in a gait cycle. These angular references, taken from [10], are used as reference signals for the motion control of ALLEX.

Fig. 2 shows the architecture of the proposed control system. The centralized controller, implemented in a Raspberry Pi, calculates and transmits, via the CAN bus, the gait angular biomechanics (set- points) to the DCs at each joint. The joint actuators are composed of a motion device (brushless motor + driver), and a sensing system. Table 1 shows relevant characteristics of the selected actuators for this prototype. The speed and torque requirements at each joint are not directly covered by the motors. Therefore, a mechanical coupling system based on planetary and cycloidal gears are used.

2.1 Centralized Controller

The Raspeberry Pi is able to manage up to 127 devices attached to the CAN bus. This device is in charge of generating and transmitting the angular references (set-points) to the DCs, as well as to receive and process sensed signals from the actuators at each joint, such as: position, speed, electrical current, and electromyographic (EMG) signals. Since the Raspberry Pi per se does not have a CAN interface, the PiCANv2 module is used to enable the CAN communication.

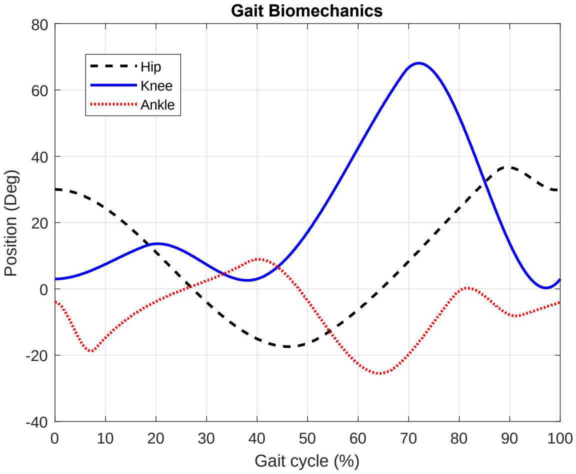

Figure 1: Non-pathologic gait biomechanics

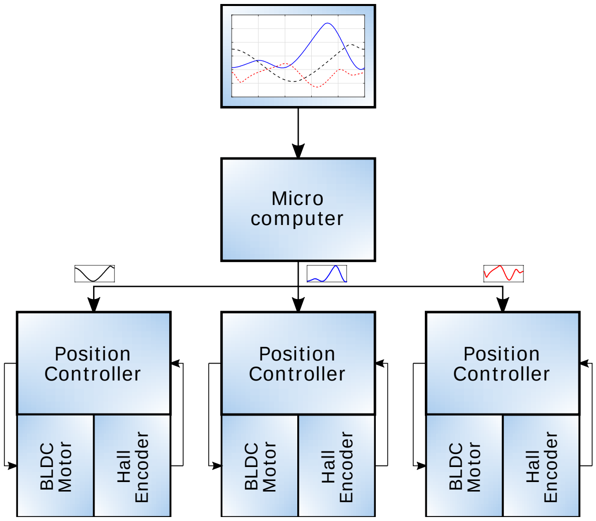

Figure 2: Control architecture of the ALLEX prototype

2.2 Distributed Controllers

The DC's topology is common for each joint, which involves two control loops, as follows:

- *Current regulation*. An actuation system requires torque control; therefore, the control variable is naturally the current of the motor, as shown in Fig. 3. This current control loop uses a PI with anti-windup algorithm with sampling period of T = 0.04 ms.

- *Position regulation*. The current control loop operates inner the position controller. Fig. 4 shows the block diagram of this control scheme. The main control loop uses a PID with anti-windup algorithm with a sampling period ten times slower than the inner loop. A feedforward strategy is also added to this control scheme in order to better compensate friction forces, and inertia. Additionally, a parabolic interpolation applied to two consecutive points received from the reference sent by the CC, is executed to guarantee constant accelerations and decelerations during the motion.

2.3 Communications Architecture

The CAN protocol is typically used in small range and real time applications. The communications scheme of the joint electronic drivers (EPOS4 from Maxon) use CAN in the lower layers of the OSI model, while in the application layer it is used CANopen [11]. The CANopen bus, for the ALLEX prototype, is configured with a transmission rate of 1 Mbps in the high-speed channel. Fig. 5 shows the network topology implemented. This protocol directly accesses the configuration and operation data from the devices attached to the CAN bus, by using service data objects (SDO). Fig. 6 shows the composition of the link layer frames, as well as the SDO messages which correspond to the application layer.

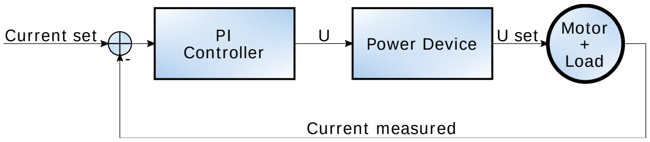

Figure 3: Current regulation loop

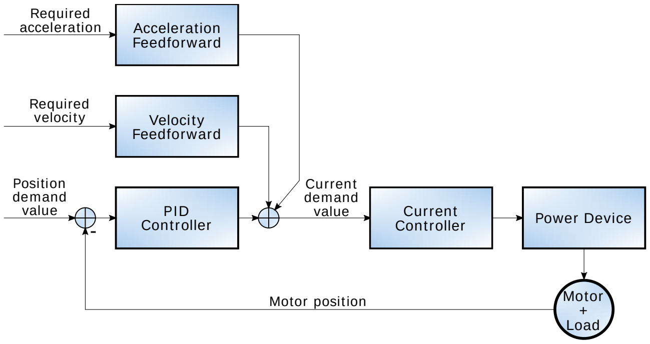

Figure 4: Position control main loop

2.4 Mechanical Design

The ALLEX prototype uses aluminum in the links, while the multiplication systems are built by using steel. The links are able to adjust their length through a telescopic bar mechanism, whose maximum length is 1.2 m.

- *Multiplication system*. This system, also known as reduction system, provides a greater output torque while reduces the output speed in comparison with the input. A cycloidal reduction system (Fig. 7) is used in the hip, while the knee and ankle use planetary gears (Fig. 8). Table 2 describes briefly the main features of the multiplication systems used in each joint.
- *Assembly criteria*. The final assembly of the prototype involves developing cases, the wiring system, and printed circuit boards (PCB). The cases are designed to cover the joint actuators (motor, driver, PCBs, and wires). The cases were built by using the Robo R2 3D printer. The wiring system and the PCBs were designed so they can be interchangeable, i.e. any actuator out of the three available for this prototype can operate interchangeably at any joint (hip, knee, and ankle).

Table 2: Main features of the multiplication systems

Feature	Hip joint	Knee/Ankle joint
Mechanical configuration	Cycloidal	Planetary gears
Reduction relationship	196:1	42.8:1
Bearings loading capacity	75 kg	75 kg

3. EXPERIMENTAL RESULTS

The experimental results presented in this section involves evaluating the performance of the prototype throughout a full gait motion stage, whether the exoskeleton operates without any load or carrying some weight. Fig. 9 shows a complete gait motion phase developed by the ALLEX prototype.

The results are evaluated separately for the control system and the communications network.

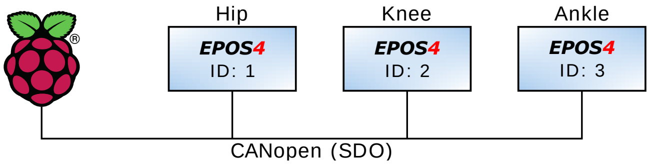

Figure 5: Communications network of ALLEX

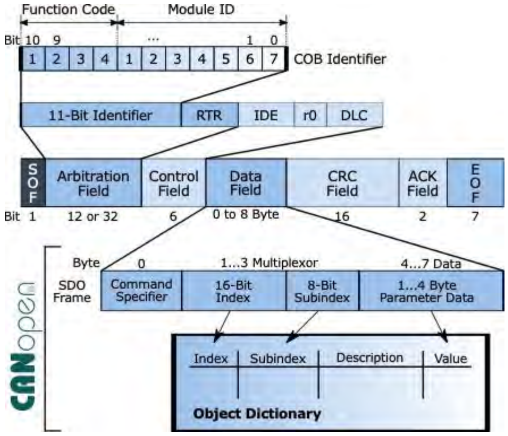

Figure 6: Link layer CAN configuration & SDO frame

3.1 Control System Performance

The testing scenarios to analyze the performance of the position control system are two: i) operation without any load; ii) operation while carrying three masses (5 kg each) near each joint. Additionally, three different speeds for completing a full gait motion cycle were tested, i.e. 4, 7, and 10 seconds of duration of the gait cycle. Nevertheless, the results obtained for the speed corresponding to the prototype completing the full gait cycle in 4 seconds are the only one considered, since the trajectory tracking for this case shows a slight deviation from the reference, while the other two cases showed a near perfect tracking performance.

- *No load operation*. The results of this test show a very good tracking performance of the control system. Fig. 10 shows the time response of the three joints during the gait cycle.
- *Carrying a 15 kg weight*. The 15 kg weight is distributed equally near each joint. The purpose is to emulate a similar weight than a lower limb, in order to test the prototype under realistic operating conditions. Fig. 11 shows a comparison of the tracking error for both tests (with and without load). The results show a better tracking performance for the no-load operation, while the tracking performance when the prototype carries a load keeps a low total mean square deviation of 0.6 degrees.

On the other hand, the performance of the energy consumption is different for each test. Table 3 shows a summary report of the current consumption for both tests. It is worth noticing that the current consumption when the prototype carries weight is larger than the one reported without any load. For instance, in average the hip actuator increases its consumption in 29%, the knee actuator increase is 112%, and the ankle actuator increase is 62%. It is remark- able that the smallest increase in current consumption corresponds to the hip actuator, where a cycloidal gear system is installed in contrast with the other two joints which have planetary gears.

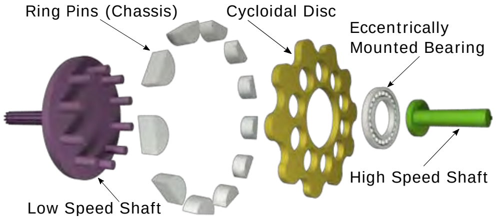

Figure 7: Main components of the cycloidal gear

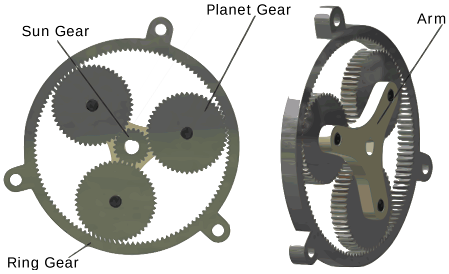

Figure 8: Main components of the planetary gear

Table 3: Current consumption during operation of ALLEX

	No load (mA)			15 kg load (mA)		
	Max	Avg	Min	Max	Avg	Min
Hip	3021	889	1	3173	943	22
Knee	3479	1041	2	6990	2281	1
Ankle	969	310	5	1289	421	2

The articular values are satisfactory, in what regards the gait biomechanics tracking. Nevertheless, it is remarkably the overall performance of the hip joint, since the multiplication system used for this joint offers a better performance than the ones used for the other two joints. This reduction system consists of a cycloidal system, whose movement is based on an eccentric shaft with a progressive ball bearing within the shell of the gear. The efficiency of the multiplication system for torque increase is 87% in comparison with the planetary gears, as reported in Table 4.

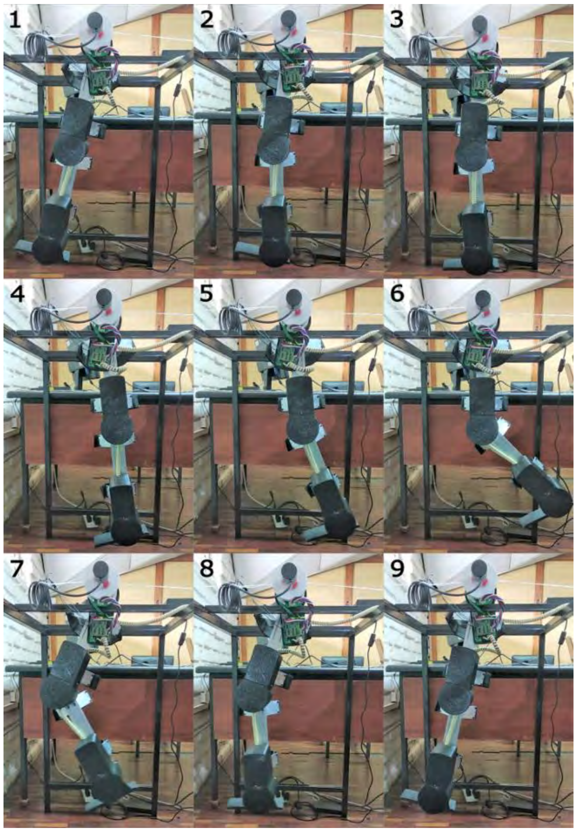

Figure 9: Operating cycle of ALLEX for gait biomechanics tracking

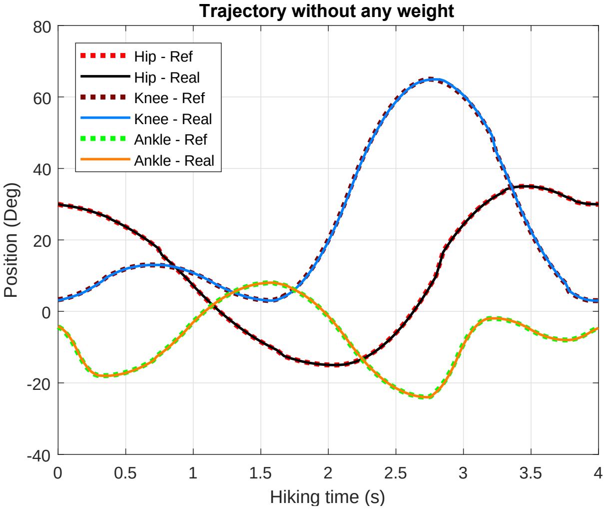

Figure 10: Joints trajectories during the no load operation

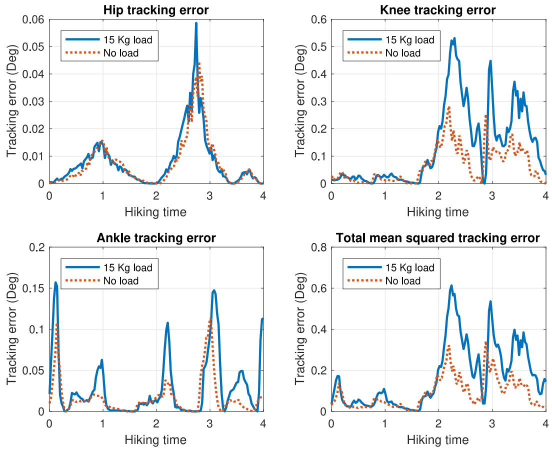

Figure 11: Tracking error developed in the prototype joints during the walk cycle

Table 4: Torque estimation at each joint during operation

	No load (Nm)			15 kg load (Nm)		
	Max	Avg	Min	Max	Avg	Min
Hip	41.74	0.01	13.67	43.84	0.3	13.03
Knee	5.49	0.1	1.64	11.04	0.2	3.6
Ankle	1.53	0.08	0.49	2.04	0.3	0.67

3.2 Communication System Performance

The experimental tests on the communications system consist in the capture of the message packages of the CAN bus during the operation of the ALLEX prototype. The purpose of these tests is to confirm that the packages sent through the bus use the SDO protocol without any losses. Additionally, the transmission speed of the data is evaluated as well as the processing speed of the centralized controller.

• *CAN messages with SDO protocol*. By using the traffic analyzer *Wireshark*, a message sent from the CC to the DCs was captured. Regardless of what type of function is sent to the motor driver (EPOS4), the master unit sends two messages, and receives one in return from the slave unit. Table 5 shows the two first mes- sages

- sent from the centralized controller to the DC located at the knee joint, while the third messages corresponds to the response sent from the slave unit (knee joint) to the master unit.

To better understand the data transfer and the messages structure of Table 5, the messages are split in hexadecimal representations. Tables 6 and 7 present the translation of the messages in accordance with the SDO structure. Every message structure to be sent through the CAN bus of the ALLEX prototype has a similar structure, with differences in the identification fields, and the data accessed from the object dictionaries of every DC.

- *Transmission delays in the CAN bus*. There are two kind of messages sent to the slave units (DCs) at each joint: i) setpoint update for the position control system; ii) query command of the joint variables values. The transmission delay for these messages depends on the communication speed and the processing time in the centralized controller (Raspberry Pi). The transmission delay was measured by capturing the time stamp of the messages in Wireshark, while the processing time is measured by using a chronometer in the code of the centralized controller.

The communication delay is less than 1 ms, which includes transmission delay plus DC's processing time. On the other hand, the processing time of the centralized controller, for calculating the motion setpoints for the DCs in accordance with the gait biomechanics, is larger and spreads in a range between 2 ms to 32 ms. The main issue of this difference in response times occurs when the stack of the communication protocol SDO is overflow due these processing speed differences. The stack overflow provokes lost in synchronism, which potentially diminishes the accuracy of the position tracking of the ALLEX prototype. A potential solution for this issue is to use a deterministic operating system in the centralized controller, such as ROS. Table 8 presents average processing times during the operation of ALLEX.

Table 9 presents some limitations of the prototype discussed throughout this paper, as well as some future works for solving these disadvantages.

Table 5: SDO message captured by using *Wireshark*

Time	Identifier	Data
0.000000	0x602	40-64-60-00-00-00-00-00
0.000359	0x602	40-64-60-00-00-00-00-00
0.000847	0x582	43-64-60-00-9a-3a-00-00

Table 6: Message sent from the CC to the DC at the knee

	Bytes sent	Analysis
Command specifier	0x40h (0x01000000b)	Indicates that data from the objects dictionary is required
Index	0x6460h	The index value of the dictionary is 0x6064 (knee angular position)
Subindex	0x00h	The subindex value of the dictionary is 0x00h
Data	0x00000000h	No message is sent, since the command corresponds to a query

Table 7: Response message from the knee DC to the CC

	Bytes sent	Analysis
Command specifier	0x43h (0x01000011b)	Indicates that data was read from the objects dictionary
Index	0x6460h	The index value of the dictionary is 0x6064 (knee angular position)
Subindex	0x00h	The subindex value of the dictionary is 0x00h
Data	0x9A3A0000h	Data value 0x15002d, which represents the knee angular position

Table 8: Transmission delay over the CAN bus vs. processing time of the centralized controller

Message type	CAN bus time (μs)	Processing time (ms)
Joints motion	636.45	32.18
Data query	847.13	2.94

Table 9: Current limitations of ALLEX

Type	Description	Possible solution
Mechanical: Multiplication system	The planetary gears installed at the knee and ankle joints do not offer enough output torque to carry large weights, such as a leg from a patient with a weight greater than average (70 kg)	Replacement of the planetary gears for cycloidal multiplication systems or harmonic drives with a reduction relationship of at least 1:100
Mechanical: Exoskeleton frame	The exoskeleton total weight, including the energy system (batteries) is near 20 kg	Redesign the exoskeleton frame by using lighter materials, such as glass fiber
Hardware: Centralized controller	The messages latency is variable, and in under certain circumstances this time is high, which eventually provokes lost in synchronism	Develop the centralized controller algorithm in a real-time operating system, and replace the SDO frames structure for the process data objects (PDO) structure

4. CONCLUSIONS

The majority of components used to build this prototype are of specialized technology for the development of robots. Therefore, a good overall performance is expected, although several issues related to current consumption in the knee and the ankle joints were analyzed when the prototype carries weight. Additionally, the embedded platform used for the deployment of the centralized controller did not offered determinism in the execution, which caused loss of synchronism during the transmission of motion commands for the joints.

The overall performance of the ALLEX prototype while tracking a gait biomechanics trajectory is correct, and seems to be suitable for automated repetitions during physical rehabilitation for recovering gait in patients with incomplete SCI. The approximate cost of ALLEX is $2,500 USD.

5. ACKNOWLEDGEMENTS

The authors would like to thank the Research Direction of the University of Cuenca, Ecuador (DIUC Dirección de Investigación de la Universidad de Cuenca) by sponsoring the project: Design and development of a lower limb exoskeleton.

6. REFERENCES

[1] K. Nas, “Rehabilitation of spinal cord injuries,” World Journal of Orthopedics, vol. 6, no. 1, p. 8, 2015. [Online]. Available: http://www.wjgnet.com/2218-5836/full/v6/i1/8.htm

[2] G. Carpino, A. Pezzola, M. Urbano, and E. Guglielmelli, “Assessing Effectiveness and Costs in Robot-Mediated Lower Limbs Rehabilitation: A Meta-Analysis and State of the Art.” Journal of healthcare engineering, vol. 2018, p. 7492024, 2018. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/29973978http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC6009012

[3] A. Rojas, A. Farfan, E. Mora, L. I. Minchala, and S. Wong, “Assessing the SNR Influence in the Estimation of the Mean Frequency of Lower Limbs sEMG Signals,” IEEE Latin America Transactions, vol. 16, no. 8, pp. 2108–2114, Aug. 2018. [Online]. Available: https://ieeexplore.ieee.org/document/8528223/

[4] J. Li, G. Chen, P. Thangavel, H. Yu, N. Thakor, A. Bezerianos, and Y. Sun, “A robotic knee exoskeleton for walking assistance and connectivity topology exploration in EEG signal,” in 2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob), Jun. 2016, pp. 1068–1073.

[5] P. Félix, J. Figueiredo, C. P. Santos, and J. C. Moreno, “Electronic design and validation of Powered Knee Orthosis system embedded with wearable sensors,” 2017 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC), pp. 110–115, 2017.

[6] D. Sanz-Merodio, M. Cestari, J. C. Arevalo, and E. Garcia, “A lower-limb exoskeleton for gait assistance in quadriplegia,” in 2012 IEEE International Conference on Robotics and Biomimetics (ROBIO). Guangzhou, China: IEEE, Dec. 2012, pp. 122–127. [Online]. Available: http://ieeexplore.ieee.org/document/ 6490954/

[7] M. Cestari, D. Sanz-Merodio, J. C. Arevalo, and E. Garcia, “An Adjustable Compliant Joint for Lower-Limb Exoskeletons,” IEEE/ASME Transactions on Mechatronics, vol. 20, no. 2, pp. 889–898, Apr. 2015. [Online]. Available: http://ieeexplore.ieee.org/document/6826501/

[8] R. Lu, Z. Li, C. Su, and A. Xue, “Development and learning control of a human limb with a rehabilitation exoskeleton,” IEEE Transactions on Industrial Electronics, vol. 61, no. 7, pp. 3776–3785, July 2014.

[9] P. Joudzadeh, A. Hadi, K. Alipour, and B. Tarvirdizadeh, “Design and implemen- tation of a cable driven lower limb exoskeleton for stair climbing,” in 2017 5th RSI International Conference on Robotics and Mechatronics (ICRoM), Oct 2017, pp. 76–81.

[10] C.-Y. Ko, J. Ko, H. J. Kim, and D. Lim, “New wearable exoskeleton for gait rehabilitation assistance integrated with mobility system,” International Journal of Precision Engineering and Manufacturing, vol. 17, no. 7, pp. 957–964, Jul. 2016. [Online]. Available: https://doi.org/10.1007/s12541-016-0117-6

[11] “CAN in Automation (CiA): CANopen.” [Online]. Available: https://www.can- cia.org/canopen/