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METHODS

Bioinspired Hierarchical Electronic Architecture for Robotic Locomotion Assistance: Application in Exoskeletons

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ABSTRACT This paper presents the conceptualization, design and development of a bioinspired electronic architecture based on the human motor system for the control of mobility assistance systems, such as assistance or rehabilitation exoskeletons. The proposed architecture is divided into three hierarchical levels: perception-intention, pattern generator, and execution, facilitating modularity, scalability, and parallelism in the execution and operation of the system. ROS2 was chosen as the middleware for communication management due to its ability to handle a large amount of data, robustness, and scalability. For validation in a real world scenario, the proposal was implemented in the gait rehabilitation robotic platform Discover2Walk. Among the advantages offered by this architecture, we highlight greater modularity, improved compatibility with programming languages, and scalability, in addition to ease of supervision and control. The architecture presented can be adopted in future robotic platforms and exoskeletons with built-in interoperability.

INDEX TERMS Rehabilitation technology, ROS2, exoskeletons, bioinspired electronics, human gait, lower limb, modular design, hierarchical control.

I. INTRODUCTION

Deficiencies in human gait, such as those caused by strokes, spinal cord injuries, and cerebral palsy, are a major source of disability worldwide [1]. The ability to walk is an essential part of daily life, and doing so independently is associated with better health outcomes and quality of life [2]. Unfortunately, people with mobility issues often have difficulty achieving independent gait. In this context, exoskeletons for rehabilitation and gait assistance, i.e., wearable devices that can provide mechanical assistance for movement, have emerged [3], [4].

Since their inception, exoskeletons have been used as mechanical devices to rehabilitate and improve the function of the limbs. They can be of great use to people with mobility issues, as they enable the restoration of limb functionality, resulting in better movement and greater strength, thus improving the quality of life of the user [5].

These devices can be controlled in different ways, for instance, (1) sensors that detect body movement and then activate or deactivate the exoskeleton; (2) remote controls so that an external operator activates or deactivates the device; and (3) brain-machine interfaces, where the user controls the exoskeleton by detecting patterns obtained by EEG or EMG sensors [6], [7].

Although the control algorithms for robotic exoskeletons share common traits that can be used for their classification and analysis [6], this homogeneity is not present in the electronic architecture of these devices. The control electronics for each system are defined by different developers. Thus, each exoskeleton has its own control and electronic architecture, which may be more or less inspired by biological

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TABLE 1. Comparison of technologies employed in various exoskeleton implementations, according to electronics and communications.

Exoskeleton	Electronics			Communications
	High Level	**Middle Level**	**Low Level**	
HAL-3 [37]	PC - Linux RTOS			-
N.N* [38]	PC - Debian Linux and CIO-DAS08/JR-AO IO-CARD			-
RoboKnee [39]	Ajile aJ-PC104			-
MindWalker[40]	PC – MATLAB		Microcontroller Drive	EtherCAT
N.N* [41]	Dspace MicoLabBox			-
CP-Walker [42]	EEG – Laptop	PC-104		CAN
N.N* [43]	Manual Input (Laptop)	Teensy 3.6		Bluetooth (Alto Nivel)
ExRoLEG[44]	Manual Switch	Atmel Mega 2560		-
Symbitron [45]	Intel NUC5i5RYH		Driver Controller	EtherCAT
AGoRA [46]	Raspberry PI		EPOS 4	I2C (Low Level) ROS(High Level)
H3 [47]	Intel NUC7i7BNH		Technaid Controller	CAN (Low Level) ROS (High Level)
H2 [48]	Smartphone - Laptop	H2-ARM Board	H2-Joint	CAN
LOPES II[49]	Computer	xPC Target	RT -Linux - microcontroller	TCP - UDP - EtherCAT
WAKE-up[50]	NI MyRio	Mc Pic32	Dynamixel Controller	RS232
Atlas 2020[51]	PC/Tablet	NI MyRio	Microcontroller ATMEL	I2C
P-LEGS [52]	PC/Laptop	SBC	ARM Cortex M4	CAN- Serial
Prex [53]	Laptop	Teensy 3.2	Servocontroller	Bluetooth

*N.N : No Name

processes but generally does not allow the exoskeleton to be modular or adaptable to new developments.

This article focuses on the conceptualization, design and development of a generalized electronic framework for lower limb robotic exoskeletons aimed at facilitating modularity, scalability, and parallelism in the system's execution and operation. To achieve these characteristics, we opted for conceptualization of the system based on biological models. The inspiration from biological processes, called biomimicry, is an interdisciplinary approach that seeks solutions to technological, social, and environmental challenges by imitating and adapting models, systems, and natural processes [8], [9]. Human gait is an example of a natural model that has been perfected over the centuries and that has been applied to the design of robots and exoskeletons. Bioinspired architecture allows these devices to be more efficient and better adapted to their environment. Moreover, the modularity of the human locomotion system, with its defined levels and specific functions, offers an advantage in interacting with human beings, thus achieving almost complete interaction with the user.

In our study, the nature of gait will be used as a model for inspiration, from its conception to its execution, to develop a new proposal for electronic architecture. Finally, the proposed framework will be designed and implemented in a real exoskeleton prototype for its validation and evaluation.

II. STATE OF THE ART. EXOSKELETON CONTROL ELECTRONICS

Table 1 summarizes the different systems that have been analyzed in terms of their electronic components and control strategies. The table shows that each exoskeleton is based on specific architectures designed for particular applications. These are our main findings:

A. DIVERSITY OF CONTROL PLATFORMS

There is no dominant platform or operating system for high-level control of exoskeletons. These range from PCs running various flavors of Linux (with RTOS, Debian, Ubuntu) to software platforms like MATLAB, and from more compact systems such as Raspberry Pi to more specialized controllers such as Dspace MicoLabBox or EEG-based systems.

B. DIVERSITY OF MICROCONTROLLERS

The controllers also vary widely, from general-purpose solutions such as Microcontrollers or Atmel Mega 2560 to more specific solutions such as Technaid Controller or H2-ARM Board.

C. COMMUNICATIONS

While there is a wide range of communication options that can be used, CAN (Control Area Network) is a commonly chosen option in several studies. In addition, EtherCAT and Bluetooth are popular choices, while other implementations use I2C and RS232. In some cases, both TCP and UDP are used in the same system but for different data flows and applications.

Given the diversity of components and communication systems employed in exoskeletons (Table 1), it is clear that a lack of standardization in the field can limit the scalability, synchronization, and modularity of these devices:

- **Scalability** is essential to ensure that exoskeletons can adapt to different applications and diverse users. Without standardization, scaling can imply redesigning components or implementing entirely new communication systems, which is costly and time-consuming.

- **Synchronization**, or the ability of components to communicate with each other efficiently and accurately, is fundamental for the effectiveness and safety of exoskeletons. The standardization of communication systems can greatly improve a device's ability to synchronize the actions of its components.
- **Modularity**, which allows for customization and easy replacement of components, can also benefit from standardization. A standardized design framework will allow for the exchange of modules between different exoskeletons, improving a device's ability to adapt to users' specific needs and facilitating repair and maintenance.

In conclusion, the standardization of the components and communication systems of exoskeletons is essential for the future development of the field. This will enable these devices to be more scalable, synchronized, and modular, improving their effectiveness and adaptability to the individual needs of the users. To meet this goal of standardization, our proposal focuses on developing a modular and scalable architecture that can adapt to different applications and enable system expansion in the future. Within this approach, the aim is not only to improve the efficiency and performance of exoskeletons but also to make them more accessible and versatile for use in different environments and applications.

III. HUMAN GAIT AS A MODEL OF INSPIRATION

Walking is a complex activity that requires the functional integration of a large group of sensory and motor neurons [10]. Despite individual differences, human gait shows a characteristic pattern [11]. Among neurophysiologists dedicated to the study of locomotion, there are two theories about the generation of gait: the first considers the reflex as a fundamental part of the generation of gait [12], while the second is based on the existence of a specific system for locomotion [13] due to the gait movements obtained for spinal cats with sections in their dorsal roots. It is believed that in humans, the central pattern generator (CPG) is distributed throughout the spinal cord and has autonomous circuits on each side for the right and left legs [14]. Additionally, the ability to generate rhythmic patterns involves an architecture of interconnected burst-generating elements [15].

Figure 1 shows a schematic representation of the neural mechanisms underlying human bipedal gait and how they are hierarchically organized to generate locomotion [16]. In hierarchical order, the lowest level is the sensorimotor system, where correct muscle activation is fundamental for gait, leading to the contractions and relaxations of agonist and antagonist muscles playing an indispensable role. Thus, the myotatic reflex or stretch reflex is responsible for motor action. This level is responsible for handling the musculoskeletal system of people [17].

The next hierarchical level of the locomotor nervous system is the CPG. This is a set of spinal neurons that largely control locomotion; this system was initially studied by Charles Sherrington and Thomas Graham [18]. The modulation of movement patterns occurs at the higher hierarchical level, in the motor and premotor cortex, the cerebellum, and the brainstem [18]. The latter regulates both the central pattern generator and the myotatic reflex mechanism. Likewise, at the supraspinal level, information is obtained from the vestibular and visual systems, which helps maintain balance and orientation [20]. Additionally, movement patterns are regulated by muscle spindles, Golgi tendon organs, and afferent feedback that arises from cutaneous mechanoreceptors [17], [21].

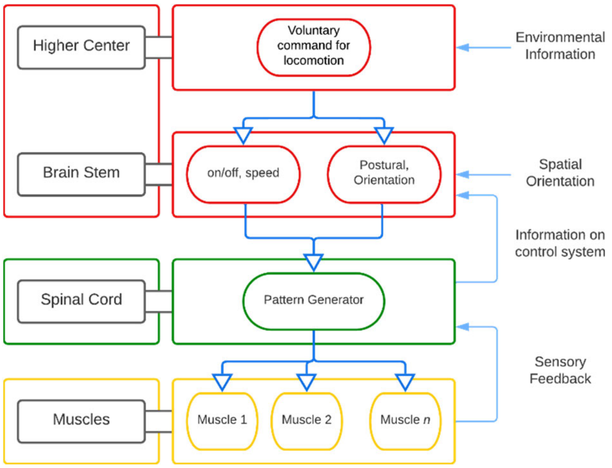

FIGURE 1. Schematic representation of the neural mechanisms. Adapted from Nakazawa, [16].

IV. PROPOSAL FOR A BIOINSPIRED MODULAR ELECTRONIC ARCHITECTURE FOR THE CONTROL OF LOWER LIMB EXOSKELETONS. TECHNICAL REQUIREMENTS

Figure 2 shows this manuscript's proposal for a generalized framework that is inspired by a model described in [22]. This model proposes a bioinspired architecture that is divided into three levels and uses concepts of biomimicry to imitate how the human nervous system controls walking.

High level: At the high level of the architecture called "perception - intention" (see Fig. 2), the controller must perceive the user's intention of movement, enabling the user to manipulate the system, the type of movement, and its parameters. Typically, exoskeletons can switch between various operating modes, depending on the desired type of activity and environment [6]. Inputs at this level can be trigger events or Boolean-type inputs, either through a graphical interface or physical buttons, or they could even be artificial intelligence algorithms capable of predicting the intention of the user [6], [22]. At this level, the controller's runtime is not critical for locomotion: the human reaction time to an auditory stimulus ranges between 140-160 ms, to a visual stimulus between 180-200 ms, and to touch of 155 ms [23], [24], [25]. In this way, the high-level electronic system algorithms should run in time frames ranging between 140-2 200 ms (7-5 Hz).

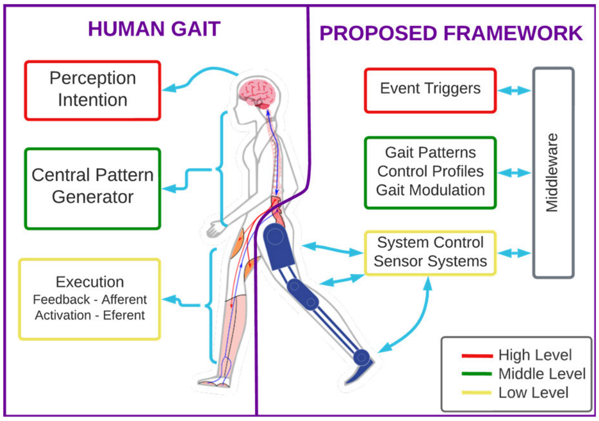

FIGURE 2. **Generalized Framework for the conceptualization of the architecture. On the left, the three hierarchical levels studied in human walking are observed. On the right, the proposed conceptual framework; and how each of the hierarchical levels and the conceptual framework interacts with a human.**

Middle level: (Central Pattern Generator, see Fig. 2) the purpose is to use the user's intentions to generate the references that must be reached by the lower level, whether they are controlled in terms of position, speed or torque. At this level, the system can have one or more control systems, which can track walking patterns, in which each system contains the necessary kinematic chains for the global system to function correctly when interacting with the human. The mid-level control also coordinates the movement of multiple motorized joints or between multiple devices [26]. It is estimated that the speeds of the nerves in the lower limbs range between 40 and 45 m/s [23], [24], [25], [27]. Considering that the average estimated length of these nerves is approximately 70 cm [28], it is concluded that the minimum frequency for correct interaction with healthy human movements ranges between 57.14 and 64.28 Hz ($\approx$ 60 Hz). It is also at this medium level where the algorithms for the modulation and generation of walking will be executed. These algorithms will have to work simultaneously, so it is proposed to use microprocessor systems capable of supporting multithread execution. In addition, these systems must have standard communication systems with low latency and high speeds to ensure the synchronization of information at the different levels.

Low level:(Execution, Fig. 2): this level is responsible for controlling each of the actuator devices to follow position, speed, or force setpoints. The references that reach this level are those sent by the middle level. Each actuator or group of actuators will have its own controller to perform a specific task, so this controller must take into account the kinematic and dynamic properties of the system to be commanded. In turn, similar to the human body, each actuator can be subject to the measurement of several sensors, be they encoders or systems for measuring the applied torque, which will provide information to the user to achieve robust control. The accuracy in the response time of closed-loop control is crucial in the discrete-time domain to achieve optimal control. To this end, it is proposed to apply a sampling frequency of 1 kHz to detect and carry out real-time adjustments in the walking cycle.

A. COMMUNICATION AND SYNCHRONIZATION

An intermediate agent is proposed to interconnect each of the control levels presented. This is a piece of software that is able to manage data, messaging, and authentication regardless of the hardware, software, or operating systems used. This tool allows for better synchronization and improves the quality of service. This system abstracts from the complexity and heterogeneity of existing communication networks within each hierarchical level, thus achieving a modular communication medium [29].

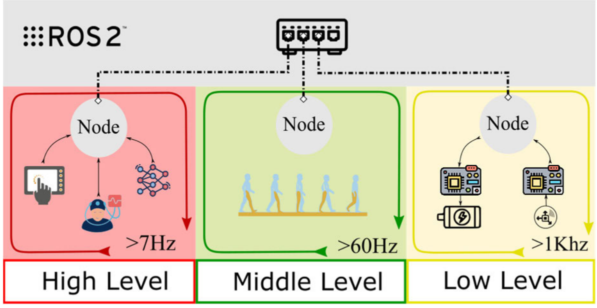

FIGURE 3. **Generalized Framework of the proposed electronic architecture.**

Here, we propose ROS2 (Robot Operating System), [30], as a solution for this intermediate agent. ROS2 provides hardware abstraction, low-level device control, and node, message, topic, and service handling. It is based on a graph architecture where processing is performed in nodes that can receive, send, and multiplex messages from sensors, control, states, planning, and actuators at different frequencies via an Ethernet network. Figure 3 illustrates the conceptualization of the framework proposed for the electronic architecture, dividing it into three hierarchical levels that follow the neural control of walking, each with its minimum frequency, and intercommunicated through ROS2.

V. PRACTICAL IMPLEMENTATION OF THE CONCEPTUAL FRAMEWORK IN A REAL ROBOTIC SYSTEM

We will use the Discover2Walk robotic system as a testing bench for the concept defined in the previous section. Discover2Walk (D2W) [31] is a robotic system designed to help children with cerebral palsy experience walking and explore their environment. D2W is a device with flexible actuation whose structure adapts to the physical development of patients (see Fig. 4). The function of the robotic system is to control the movement of the lower limbs (pelvis and ankles) during walking. Allowing the child to discover how to walk while adjusting his own gait to that of a healthy child, correcting his postural impairment.

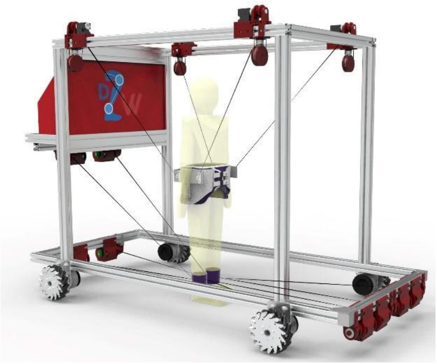

FIGURE 4. Discover2Walk robotic system. A prototype of the flexible exoskeleton for the study of a child's movement.

TABLE 2. Distribution of actuators and sensors in discover2walk.

SYSTEMS	ACTUATORS	SENSORS
Perception		RGBD Camera LIDAR
Traction	DC Motors X4	IMU Encoders X4 Current Sensor X4
Pelvis	DC Motors X4	Load Cells X4 IMU Encoders X4 Current Sensor X4
Ankles	DC Motors X8.	Encoders X8 Current Sensor X8
TOTAL	16 actuators	40 sensors

The D2W robotic structure must adapt to the movement the child makes, without limiting his trajectory. To do this, the external structure moves with a synchronized movement, where omnidirectional actuated wheels are used. The robot has 4 brushless motors with a power of 600 W, in addition to quadrature encoder-type position sensors and current sensors. D2W also contains a cable system controlled by four motors, responsible for modifying the child's pelvis movement, in addition to supporting his weight; for this, it uses 4 load cells for tension and compression.

Additionally, a cable-guided system has been designed to generate the trajectory of the child's movement during walking. In the robotic structure, 8 motors are placed that coordinate the tension exerted on the cables during walking (4 for each lower limb). However, due to the traction force generated, movement is transmitted at the end of the cable that falls on a harness worn by the patient. This allows for control of the child's joint position in his displacement.

Discover2Walk also contains a navigation system composed of a LIDAR and a camera that generates depth maps, which enables the system to navigate through its environment, and, thus, generate cognitive therapies in the future.

One of the primary challenges associated with the Discover2Walk robotic system is the need to achieve accurate synchronization among its various components, owing to its sophisticated design. The achievement of harmonious and real-time communication becomes of utmost importance when dealing with a combination of 16 motors and 40 sensors that function concurrently (Table 2). The successful replication of a natural, human-like stride necessitates the precise coordination of several components, including brushless motors that power omnidirectional wheels and encoders that capture position data. The occurrence of any delay or miscommunication, regardless of its small magnitude, has the ability to disturb the walking pattern, resulting in undesirable motions. These movements not only impede the rehabilitation process but also represent safety hazards to the child.

In addition, the use of a cable-guided system introduces a distinctive method for controlling the child's motion. However, the synchronization of tension among the eight motors in real time, particularly in dynamic gait situations, significantly enhances the intricacy of the system. Maintaining equilibrium between the stress exerted by the wires and the child's innate movement patterns is of utmost importance.

The incorporation of the LIDAR and camera system brings an additional level of complexity. The seamless integration of these components is essential for effective environmental navigation and prospective cognitive therapies, as it prevents the introduction of delays or inconsistencies caused by external stimuli or environmental influences. Hence, the successful integration and synchronization of these various components and systems in a live setting is a significant obstacle in fully harnessing the capabilities of the Discover2Walk robotic system.

A. ARCHITECTURE DEFINITION

Figure 5 illustrates the implementation of the theoretical framework defined in Section IV for the D2W system. In Fig. 6, we illustrate its implementation using ROS2. At the high level, there is communication between perception and intention algorithms with ROS2 services, which modify the parameters at each level. At the middle level, there is a pattern generator node that sends instructions to the nodes of the lower level. Additionally, the framework subscribes to the topics published by some lower-level nodes to modulate and modify the walk. Finally, the low level controls are operated and the different parameters of the actuators are published in addition to certain necessary variables such as the system's odometry or the measurements taken using inertial sensors or force sensors.

- High Level

For the high level, an HTML-based graphical interface was designed, which, through ROS2 services, connects with the lower levels. This interface allows for the configuration of the platform to enable adjustment to the therapeutic needs of each patient:

- The subject's anthropomorphic variables in terms of weight and height are established.

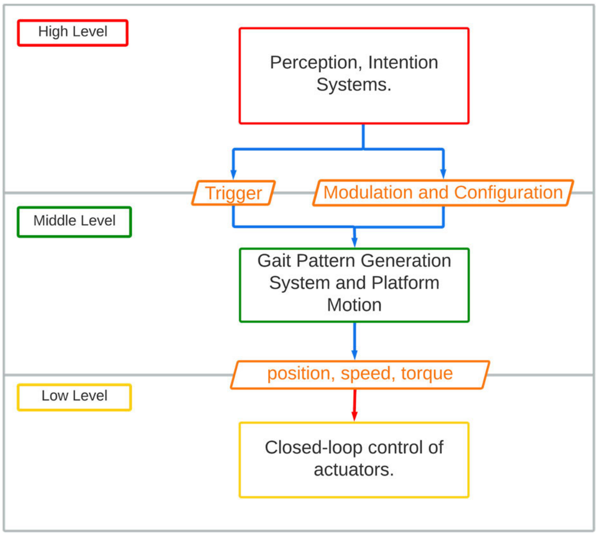

FIGURE 5. **Generalized D2W scheme.**

- The modulation parameters of the walk to be used during the therapy (impedance levels and speed) are established.
- An event trigger is sent to all nodes to initialize their execution.

In turn, the topics published at the different system levels can be monitored in real time using the graphical interface, providing feedback to the user and/or therapist. Publishing these positions in ROS2 topics can provide a remarkable advantage by enabling graphic visualization. This functionality is extremely useful, as it provides a clear and comprehensible visual representation of the three-dimensional movements of the joints. Both users and developers can observe more intuitively and in greater detail how the gait generated by the pattern generator develops and changes over time. Furthermore, by having access to this real-time graphical representation, it is possible to precisely track the evolution of the gait, which facilitates the detection of possible problems or anomalies in the process. This allows adjustments and improvements to be made more efficiently, either by modifying the parameters of the pattern generator or making adjustments in the walking speed configuration.

The event trigger can be generated in two ways: either by depressing a button on the interface or by using a BCI device using algorithms that process cortical activity. When the patient thinks about making a movement, the device detects the electrical activity generated by the brain, interprets it as the user's intention, and sends a signal to the exoskeleton to perform the preconfigured walking movement, [32].

Additionally, at the high level, we have navigation devices for environmental perception, which are responsible for sending new configurations to the middle level in terms of speed, direction and force fields in the environment.

- Middle Level

At the middle level, a single node is created: Gait_Generator _Controller. It is responsible for generating the walking patterns and for publishing and sending instructions to each control node located at the low level. Calculation of the spatial (three-dimensional) position of each joint was carried out using the algorithm proposed in [33]. This algorithm takes the walking speed and user's height as input, generating different setpoints that are sent to the controllers at the low level. In addition, it is possible to adjust the walking speed configuration in real time, which enables one to modify trajectories and create new setpoints, which are immediately sent to the low level.

This middle level node, in turn, uses a service called "GaitConfig", which sends parameters from the high level to correctly modulate the walking phases and later modifies them by sending new instructions to the corresponding low level nodes. As it is in charge of sending the instructions, a single custom message is created for this purpose called GaitSetpoints. This message includes the instructions for the controllers for the pelvis, ankle and traction subsystems. The GaitSetpoints message is generated and used to command all the instructions at the Low Level, so several internal messages are created: three-dimensional positions of the pelvis, ankle and traction, as well as walking speed.

Each node contains a ROS2 Services server. Each service modifies and configures the behavior of the node in terms of control, establishing the level of impedance and the type of control to be used. It is important to note that these services will be attended from the High Level. Likewise, these services use a confirmation response to let the user and/or therapist know that the operation modes have been accepted. If this is not the case, an error will be displayed on the graphical interface.

- Low Level

The Low Level is responsible for managing and sending walking instructions for each kinematic group. It also sends defined instructions (position, speed or torque) to each motor to achieve the movement commanded by the higher levels. For this reason, each kinematic group is implemented in a ROS2 node that executes and performs the kinematic control, achieving modularity for each system. For this purpose, three nodes are implemented at this level:

- *Pelvis_Control_Node*: This node is responsible for the control of the pelvis position and for carrying out the measurements for control of the user's weight. It uses kinematic algorithms to modify the position and rotation of the pelvis in three-dimensional space and sends instructions to the controllers of each motor. In addition, it captures and publishes the measurements made by the sensors of each motor (position, speed and current). It also uses a system composed of force sensors to monitor the tension applied to each cable of the robot for weight control and an inertial unit to obtain the real movement of the orthosis.

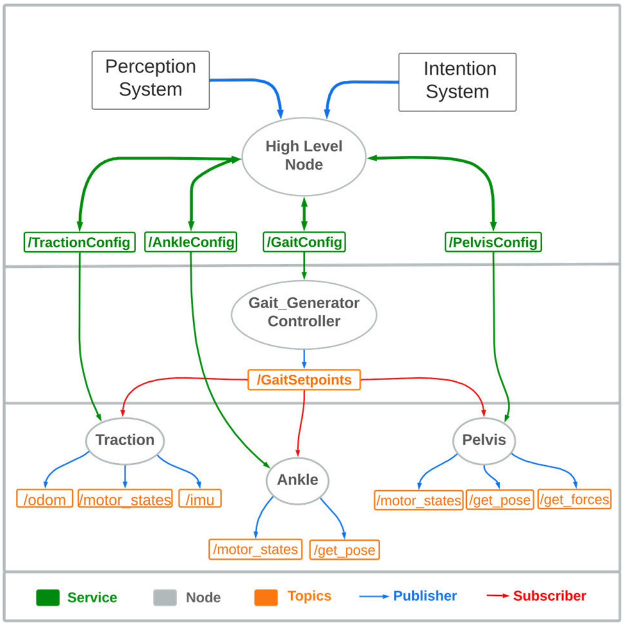

FIGURE 6. **ROS2 architecture implemented on three levels: High Level: Perception - Intention, Middle Level: Movement pattern generator, Low Level: Closed loop control of actuators.**

- *Ankle_Control_Node*: This node manages the position of the ankles at each moment of the walking cycle. It uses the necessary algorithms to calculate the position of each ankle in the three-dimensional space and in turn sends control instructions to the corresponding motors for each lower limb (4 for each one). Like the other nodes, it reads and publishes the data obtained from sensors of the motors (position, speed, and current).
- *Traction_Control_Node*: This node is in charge of controlling the omnidirectional mobile platform; it uses kinematic algorithms for movement, odometry and reading various sensors for the management and control of the motors (position, speed, current). In addition, it uses a control algorithm that, with an IMU, enables the platform to be correctly directed.

B. ELECTRONIC ARCHITECTURE

To ensure the correct operation of all the software presented above, it is essential to use hardware capable of carrying out the tasks corresponding to each level. As a result, a schematic representation of the proposed hardware architecture was prepared (see Fig. 7). In this figure, the divisions into three hierarchical levels can be clearly distinguished.

At the High Level, a Raspberry Pi 4 computer (Raspberry Pi Foundation, United Kingdom) is used to generate the web server and database. In addition, it manages the communication between perception devices and intention prediction with ROS2 through services that allow for modification of the different systems of other levels. The Middle Level is also implemented with a Raspberry Pi 4 and contains the gait pattern generating algorithms. These algorithms are executed in the Gait_Controller node.

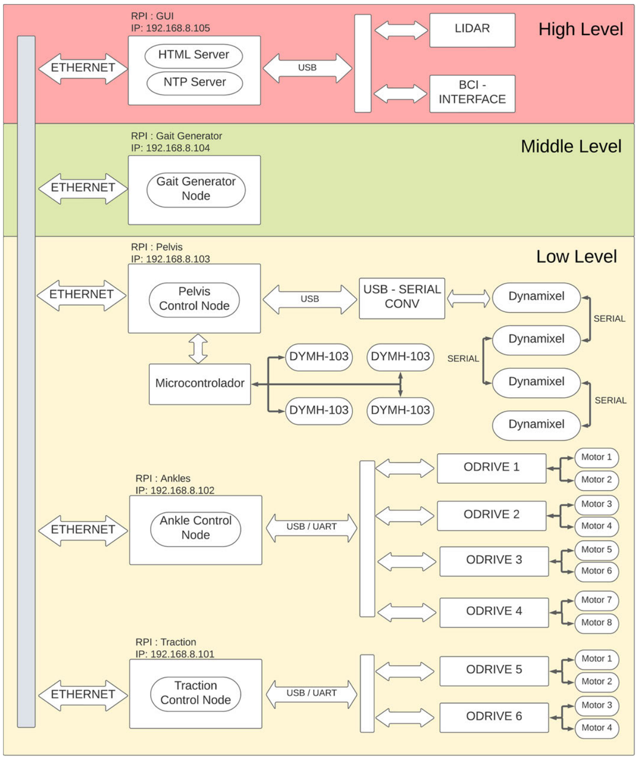

FIGURE 7. **Hardware architecture, at the Low Level the subdivision of the sections: pelvis, ankles, and traction can be seen.**

The Low Level is divided into three sections. In the first section, called "Traction" (see Fig. 7), a Raspberry Pi 4 is used that commands two ODRIVE 3.6 motor controllers (OdriveRobotics, United States). This system allows for control of the position, speed, and torque of each motor. Each controller manages two MAXON EC 90 Flat 600 W motors (Maxon, Switzerland) and an encoder that enables motor positioning. In addition, a 9-axis BNO055 IMU (Bosch, Germany) is installed, which uses sensor fusion algorithms to provide data with greater precision, which aids in the platform's odometry system.

In the second section, called "Ankles", a Raspberry Pi 4 is used to command a set of 4 ODRIVE 3.6 controllers, which handle 8 D6374 150Kv motors (OdriveRobotics, United States) with their respective AMT102-V encoders (CUI Devices, United States) of 2048 pulses per revolution (see Fig. 7).

For the third section, called "Pelvis", the following are incorporated: 4 Dynamixel XH-540 motors (Robotis, Korea) that communicate using the proprietary Protocol 2.0, a reading system for DYMH-103 load cells (Calt, China) of 20 kg each, connected with a Raspberry Pi Pico microcontroller, which conditions and sends the data from the load cells to a Raspberry Pi 4 via a serial protocol, and finally a BNO055 IMU (Bosch, Germany) that monitors the movement of the pelvis.

VI. TECHNICAL VALIDATION

The biomimetic electronic architecture proposed in this article was implemented and validated in the D2W robotic system. We defined different experiments to evaluate different aspects of our proposal:

A. Synchronization: For evaluation of our architecture's ability to enable the synchronization of the different systems in a hierarchical approach, we assessed its compliance with the requirements in terms of message timing and frequencies in the control loops.
B. Modularity: To evaluate the system modularity, we changed all the electronics responsible for the gait pattern generation in our system. The new electronics should be able to communicate with the other levels without requiring any new adjustments.
C. Scalability: In this test, we included a new actuation system (complementary to device actuators) and assessed whether we could synchronize the new system with the Discover2Walk platform.

The next section describes these tests and shows the ability of the control architecture to cope with these challenges.

A. SYNCHRONIZATION

The validation involved exposing the robotic system to stress conditions and measuring the bandwidths used, the packet transmission speed, and the message sizes within the network managed by the ROS2 communication system. Table 3 summarizes the measurements charred out for each ROS2 node at its different hierarchical levels, where each node and its topic with the network usage bandwidth, the publication frequency of each topic in ROS2, and the size in kilobytes of the message can be observed. Additionally, the frequency of each control loop in the electronic systems has been included.

OWAMP (One-way Active Measurement Protocol) was used as the protocol for measuring latencies in our network. This protocol has been designed to evaluate the one-way performance of a network and is a product of the IP Performance Metrics (IPPM) Working Group of the Internet Engineering Task Force (IETF) [34]. Through its implementation, we carried out a detailed analysis of the network and obtained latency measurements for different interconnection methods (see Table 4).

The OWAMP protocol, specified in RFC 4656 [34], has undergone a standardization process. The OWAMP specification includes a detailed description of the protocol and how measurements should be made, enabling others to implement and validate the protocol in their own systems.

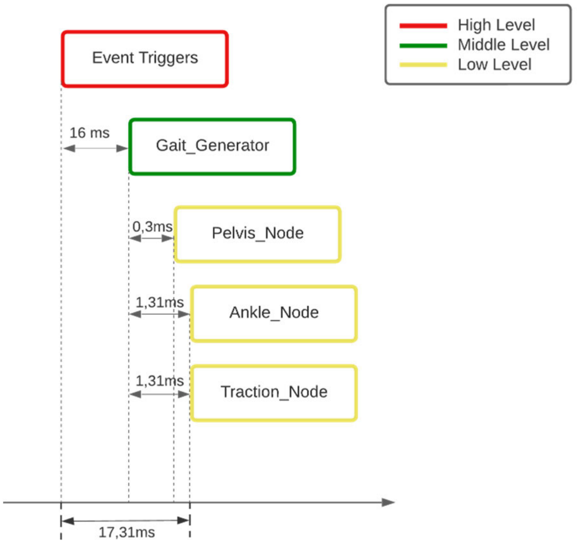

FIGURE 8. ROS2 message response times between the high, medium and low levels.

To ensure efficient communication, an internal NTP (Network Time Protocol) server was used within the network, based on Mills' proposal, [35]. This synchronization protocol ensures temporal coherence across all systems, thereby minimizing the potential for delays or errors in data transmission, which is essential for optimal robotic system performance. In addition to network-wide synchronization, we have leveraged the capabilities of ROS2 message headers, which include crucial timestamp information. This feature allows for precise tracking of the sending and receiving moments of each message, ensuring accurate interpretation upon its arrival at the destination. Furthermore, ROS2 introduces features and Quality of Service (QoS) settings to address various communication challenges, including packet loss.

Among the array of QoS policies provided by ROS2, the Reliability policy is particularly relevant to the management of packet loss. This policy dictates the middleware's behavior in the face of lost packets, offering two configuration options: BEST_EFFORT, which does not attempt retransmissions, and RELIABLE, which ensures that lost packets are retransmitted. In our implementation, we have opted for RELIABLE, aligning with our commitment to robust and dependable communication within the robotic system.

As shown in Fig. 8, the trigger event is transmitted from the upper level (High Level) to the middle level (Middle Level). The latter contains a series of gait pattern-generating algorithms that are essential for the optimal operation of our exoskeleton. The frequency at which the middle level reads the messages transmitted from the upper level is, in general terms, approximately 60 Hz. However, after closer observation and measurement of the timestamps for all received messages, we determined a real rate of 62.5 Hz. This means that for every 16 milliseconds, the middle level is able to receive and process a message arriving from the higher level.

On the other hand, the pattern generator's function is to calculate and send new positions to the lower level (Low Level). This level is responsible for controlling each of the exoskeleton's joints. Here, the average reading time (RMS) for each cycle ranges between 0.3 and 1.31 milliseconds (Fig. 8). This variance reflects the existence of nodes operating at a swift 0.3ms, while others function at the slower pace of 1.31ms. This range ensures a near-instantaneous

TABLE 3. Evaluation of ROS nodes and frequency control loop.

Level	ROS2 Node	Bandwidth (KB/s)	ROS2 Frequency (Hz)	Size (KB)	Frequency Control Loop (Hz)	Requirement (Hz)
High	Lidar - BCI	0,524	9,99	0,052	-	≥7
Middle	Pattern Generator	30,93	62,476	0,49	60	≥60
Low	Ankle	48,08	58.89	1,02	>1000	≥1000
	Pelvis	29,18	66,69	0,44	>1000	≥1000
	Traction	30,79	79,165	0,39	>1000	≥1000

TABLE 4. Latency measurements for different interconnection methods: Ethernet vs. Wi-Fi.

	INTERCONNECTED	
	Ethernet - Ethernet	Ethernet - Wifi
Max:	1.086 ms	167.948 ms
Avrg:	0.643 ms	48.08ms
Min:	0.0857 ms	1.453 ms

response in the actuator control system, thus ensuring precise and effective control of our exoskeleton. This efficiency in communication and control is one of the fundamental aspects that guarantee the superior performance of our system.

B. MODULARITY

A standout feature of the proposed system is its modularity. In the different suggested levels, electronic components can be interchanged without affecting any other level. The only constant that must be maintained is the communication protocol and the different types of messages established in the topics, which are based on ROS2 through an Ethernet network.

During the technical validation process, the Pattern Generator module was swapped, originally implemented on a Raspberry Pi 4, for an SBC LattePanda Delta system. It is relevant to mention that both systems operate with similar versions of the Linux operating system. Additionally, it is worth noting that specific adjustments are necessary for the new system to connect to the NTP server and thus achieve synchronization. This circumstance demonstrates the system's flexibility and its ability to adapt to different hardware configurations without compromising its functionality or performance. In addition, a significant modification was implemented in the traction system. The original omnidirectional system was replaced by a treadmill system (Fig. 9). The main goal of this change was to conduct exhaustive tests on the pattern generator and directly observe the results, eliminating the translation factor.

This procedure involved connecting the treadmill system to the ROS2 message responsible for transmitting the walking speed. It is pertinent to observe that the direction of the walk in this system was not used since the treadmill's structure itself limits such movement, restricting walk to a predetermined direction.

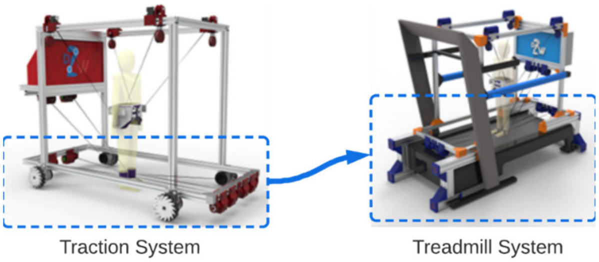

FIGURE 9. Modification of the traction system to a treadmill.

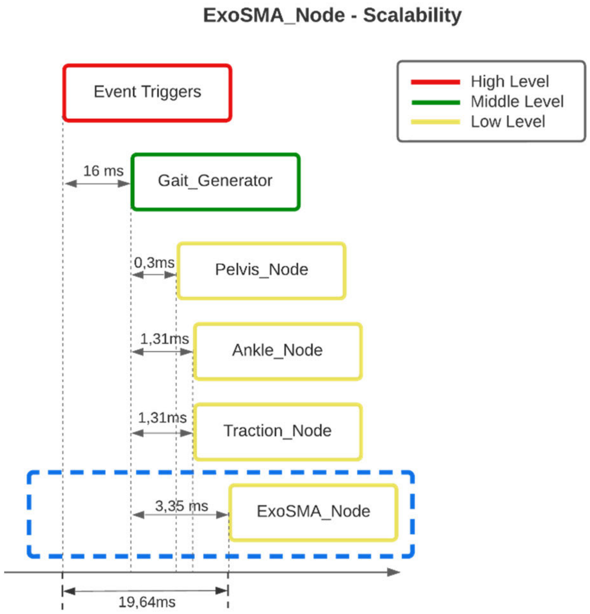

FIGURE 10. Addition of the ExoSMA_Node node that is used to manage the flexible exoskeleton.

After conducting the relevant tests, the system demonstrated optimal performance. The treadmill synced perfectly with the walking speed, allowing for real-time adjustments. This fact clearly illustrates the adaptability of the D2W robotic platform and its ability to efficiently integrate and handle different traction systems, significantly increasing its versatility and applicability in various operational conditions. The correct performance of the system after these changes demonstrates the ability of our proposal to adapt to different types of hardware.

C. SCALABILITY

The D2W robotic platform is designed to be scalable, a feature that gives it the ability to handle increasing workloads, incorporate new functionalities, and adapt to a broad spectrum of operational conditions. Scalability in terms of hardware is achieved through its modular design. Each module or component can be modified, updated, or replaced without affecting the performance of the complete system. This flexibility allows the D2W platform to integrate advanced electronic components and adapt to future technological improvements.

Regarding software scalability, the D2W exoskeleton, thanks to its middleware based on ROS2 via Ethernet, allows for the integration of new nodes or software modules as they are developed or become necessary. Likewise, ROS2 offers a range of standardized communication interfaces and provides a high degree of compatibility with various hardware platforms and programming languages.

The scalability of the D2W robot also extends to its synchronized time system, based on the Network Time Protocol (NTP). This system ensures that, as more modules or components are added to the system, all parts can maintain accurate time synchronization, a critical capability for the efficient operation of a complex robotic system.

To demonstrate the scalability feature of D2W, the integration of a flexible ankle exoskeleton designed by UC3M [36] was carried out. This system used actuators built using Shape Memory Alloys (SMA) with the aim of accurate adjustment of the ankle angle. The integration process for the D2W system involved a series of technical steps. First, the exoskeleton system was physically connected to the D2W. Subsequently, the necessary software-level configurations were carried out to ensure optimal interaction between the two systems. This involved programming the specific parameters of the exoskeleton system into the D2W configuration.

Once the physical interconnection was established, the exoskeleton system was linked to the ROS2 message that is transmitted from the D2W gait pattern generator. This connection enabled the speed and walking pattern of the D2W to directly influence the adjustment of the ankle angle provided by the exoskeleton. The result was a real-time modification of the ankle angle (see Fig. 9), effectively demonstrating the scalability and adaptability of the D2W. This achievement shows the ability of the D2W to incorporate and adapt to new modules, highlighting the practicality of its scalability in real robotic applications.

VII. DISCUSSION

This article defines a control architecture capable of mimicking certain actions of human walking. It addresses the main limitations identified in Section II: most of the current robotic solutions are organized in hierarchical levels of electronic control, which work correctly for the solutions they were designed for. However, these robotic systems contain different electronic systems that are designed ad hoc, preventing them from being modular and/or scalable. The proposed architecture is bioinspired by the human motor control system. The proposed implementation is able to generate control loops with different hierarchical levels that communicate with each other to manage complex movements. A communication architecture was developed that can achieve latency similar to that of the human biological system and requires a small bandwidth (1.12 Mbps). The latency measurements presented in this article are indicative, as there are external factors to the network that can affect the results, such as traffic load, geographical distance, and cable quality.

The choice of the ROS2 distribution (ROS2 foxy) enabled us to create a communications network for the platform so that it could be replicated at any time. It also allowed us to create a modular and hierarchical control architecture in which we can include new sensors to implement more complex processes. ROS2 tools also allow for the monitoring of the gait of patients who are using the D2W exoskeleton.

A. LIMITATIONS OF THE ARCHITECTURE

While the bioinspired architecture offers promising advancements in robotic control, it's paramount to acknowledge its potential challenges. As we delve into these intricacies, it becomes clear that alongside its many benefits, certain limitations arise that warrant consideration:

Enhanced System Complexity: While the architecture seeks to emulate human movement intricacies, it inevitably introduces an elevated level of complexity to the electronic system.

Financial Implications: Instead of streamlining expenditures, the architecture might inadvertently raise the associated costs due to its sophisticated nature.

Energy Consumption Concerns: The advanced features and capabilities might result in an uptick in energy consumption, demanding more efficient power management.

Tethering to Middleware: The system showcases a pronounced reliance on ROS2, which could pose challenges in terms of adaptability and system versatility in diverse scenarios.

Oversimplification of Natural Models: Nature and biology, in their essence, are profoundly complex. Endeavors to simulate or derive inspiration from them will, by necessity, introduce simplifications. These streamlined interpretations might curtail the architecture's precision and overall efficacy.

In light of the aforementioned limitations, it's essential to weigh the architecture's potential benefits against its drawbacks. Every technological advancement comes with its set of challenges, and in the framework of robotic solutions, the balance between complexity and utility is always delicate. While the architecture promises enhanced capabilities and a closer approximation to human motor functions, its broader applicability will ultimately be determined by how well it can mitigate its inherent limitations and cater to diverse, real-world scenarios.

VIII. CONCLUSION

The proposed improvement in the electronic architecture of devices that can assist with human walking can contribute to the creation of exoskeletons that offer more personalized therapies. Thanks to this new conceptual framework, we can highlight the following advantages:

- Greater modularity: This facilitates the creation of more complex systems and the integration of reusable software components.
- Improvements in compatibility with programming languages: ROS2 is compatible with a wide range of programming languages, allowing developers to choose the language that best suits their needs and skills.
- Improvements in interoperability: ROS2 allows for interoperability with other systems, facilitating integration with external devices and the creation of more complex solutions.
- Support for distributed applications: This architecture is compatible with the creation of distributed applications, enabling developers to create solutions that run on multiple systems and locations.
- Facilitates supervision and control: With a hierarchical system, it is easier to monitor and control activities, as each level of the hierarchy contains its own specific tasks.

The proposal presented can be applied to exoskeletons used for both assistance and rehabilitation, as it focuses on facilitating control of the device by making it similar to the motor control of walking. With this study, it is intended that future robotic platforms and exoskeletons can adopt and take full advantage of this bioinspired architecture for their control.

REFERENCES

[1] C. J. L. Murray, "Disability-adjusted life years (DALYs) for 291 diseases and injuries in 21 regions, 1990–2010: A systematic analysis for the Global Burden of Disease Study 2010," *Lancet*, vol. 380, no. 9859, pp. 2197–2223, Dec. 2012, doi: 10.1016/S0140-6736(12)61689-4.

[2] A. V. Patel, "Walking in relation to mortality in a large prospective cohort of older U.S. adults," *Amer. J. Preventive Med.*, vol. 54, no. 1, pp. 10–19, Jan. 2018, doi: 10.1016/j.amepre.2017.08.019.

[3] E. Rocon and J. L. Pons, *Exoskeletons in Rehabilitation Robotics: Tremor Suppression. Springer Tracts in Advanced Robotics*, vol. 69. Berlin, Germany: Springer, 2011, doi: 10.1007/978-3-642-17659-3_1.

[4] D. Shi, W. Zhang, W. Zhang, and X. Ding, "A review on lower limb rehabilitation exoskeleton robots," *Chin. J. Mech. Eng.*, vol. 32, no. 1, pp. 1–11, Dec. 2019, doi: 10.1186/S10033-019-0389-8/TABLES/3.

[5] J. L. Pons, *Wearable Robots: Biomechatronic Exoskeletons*. Chichester, U.K.: Wiley, 2008.

[6] R. Baud, A. R. Manzoori, A. Ijspeert, and M. Bouri, "Review of control strategies for lower-limb exoskeletons to assist gait," *J. NeuroEng. Rehabil.*, vol. 18, no. 1, pp. 1–34, Dec. 2021, doi: 10.1186/s12984-021-00906-3.

[7] M. D. Del Castillo, J. I. Serrano, S. Lerma, I. Martínez, and E. Rocon, "Evaluación Neurofisiológica del entrenamiento de la Imaginación motora con realidad virtual en pacientes Pediátricos con Parálisis cerebral," *Revista Iberoamericana de Automática e Informática Ind.*, vol. 15, no. 2, p. 174, Mar. 2018, doi: 10.4995/riai.2017.8819.

[8] H. Dicks, "The philosophy of biomimicry," *Philosophy Technol.*, vol. 29, no. 3, pp. 223–243, Sep. 2016, doi: 10.1007/s13347-015-0210-2.

[9] S. Pathak, "Biomimicry: (Innovation inspired by nature)," *Int. J. New Technol. Res.*, vol. 5, no. 6, pp. 34–38, Jun. 2019, doi: 10.31871/ijntr.5.6.17.

[10] S. T. Pheasant, "A review of: 'Human walking'. By V. T. Inman, H. J. Ralston, and F. Todd. (Baltimore, London: Williams & Wilkins, 1981.) [Pp.154.]," *Ergonomics*, vol. 24, no. 12, pp. 969–976, Dec. 2007, doi: 10.1080/00140138108924919.

[11] S. Dh. (1994). *Kinematics of Normal Human Walking*. Human Walking. Accessed: Sep. 6, 2022. [Online]. Available: https://cir.nii.ac.jp/crid/1570572700224225152

[12] C. S. Sherrington, "Flexion-reflex of the limb, crossed extension-reflex, and reflex stepping and standing," *J. Physiol.*, vol. 40, nos. 1–2, pp. 28–121, Apr. 1910, doi: 10.1113/jphysiol.1910.sp001362.

[13] T. G. Brown, "The intrinsic factors in the act of progression in the mammal," *Proc. Roy. Soc. London*, vol. 84, pp. 308–319, Dec. 1911, doi: 10.1098/RSPB.1911.0077.

[14] K. Minassian, U. S. Hofstoetter, F. Dzeladini, P. A. Guertin, and A. Ijspeert, "The human central pattern generator for locomotion: Does it exist and contribute to walking," *Neuroscientist*, vol. 23, no. 6, pp. 649–663, Dec. 2017, doi: 10.1177/1073858417699790.

[15] S. M. Danner, U. S. Hofstoetter, B. Freundl, H. Binder, W. Mayr, F. Rattay, and K. Minassian, "Human spinal locomotor control is based on flexibly organized burst generators," *Brain*, vol. 138, no. 3, pp. 577–588, Mar. 2015, doi: 10.1093/brain/awu372.

[16] K. Nakazawa, H. Obata, and S. Sasagawa, "Neural control of human gait and posture," *J. Phys. Fitness Sports Med.*, vol. 1, no. 2, pp. 263–269, 2012, doi: 10.7600/jpfsm.1.263.

[17] V. Dietz, "Proprioception and locomotor disorders," *Nature Rev. Neurosci.*, vol. 3, no. 10, pp. 781–790, Oct. 2002, doi: 10.1038/nrn939.

[18] G. E. Loeb, "Neural control of locomotion howdo all the data fit together?" *Animals*, vol. 39, no. 11, pp. 800–804, 2008.

[19] H. W. A. A. Van De Crommert, T. Mulder, and J. Duysens, "Neural control of locomotion: Sensory control of the central pattern generator and its relation to treadmill training," *Gait Posture*, vol. 7, no. 3, pp. 251–263, 1998, doi: 10.1016/S0966-6362(98)00010-1.

[20] A. Frigon and S. Rossignol, "Experiments and models of sensorimotor interactions during locomotion," *Biol. Cybern.*, vol. 95, no. 6, pp. 607–627, Dec. 2006, doi: 10.1007/s00422-006-0129-x.

[21] A. Prochazka, V. Gritsenko, and S. Yakovenko, "Sensory control of locomotion: Reflexes versus higher-level control," *Adv. Express Med. Biol.*, vol. 508, pp. 357–367, Jan. 2002, doi: 10.1007/978-1-4615-0713-0_41.

[22] M. R. Tucker, J. Olivier, A. Pagel, H. Bleuler, M. Bouri, O. Lambercy, J. D. R. Millán, R. Riener, H. Vallery, and R. Gassert, "Control strategies for active lower extremity prosthetics and orthotics: A review," *J. NeuroEng. Rehabil.*, vol. 12, no. 1, p. 1, 2015, doi: 10.1186/1743-0003-12-1.

[23] R. J. Kosinski. (Aug. 2010). *A Literature Review on Reaction Time*. [Online]. Available: http://biology.clemson.edu/bpc/bp/Lab/110/reaction.htm

[24] P. A. Vernon and M. Mori, "Intelligence, reaction times, and peripheral nerve conduction velocity," *Intelligence*, vol. 16, nos. 3–4, pp. 273–288, 1992, doi: 10.1016/0160-2896(92)90010-O.

[25] D. L. Woods, J. M. Wyma, E. W. Yund, T. J. Herron, and B. Reed, "Factors influencing the latency of simple reaction time," *Frontiers Hum. Neurosci.*, vol. 9, pp. 1–12, Mar. 2015, doi: 10.3389/fnhum.2015.00131.

[26] J. S. Lora-Millan, J. C. Moreno, and E. Rocon, "Coordination between partial robotic exoskeletons and human gait: A comprehensive review on control strategies," *Frontiers Bioeng. Biotechnol.*, vol. 10, p. 819, May 2022, doi: 10.3389/FBIOE.2022.842294/BIBTEX.

[27] R. Letz and F. Gerr, "Covariates of human peripheral nerve function: I. Nerve conduction velocity and amplitude," *Neurotoxicol. Teratol.*, vol. 16, no. 1, pp. 95–104, 1994, doi: 10.1016/0892-0362(94)90014-0.

[28] W. G. Elbarrany and F. M. Altaf, "The tibial nerve and its vasculature: An anatomical evaluation," *Int. J. Morphology*, vol. 35, no. 3, pp. 812–819, Sep. 2017, doi: 10.4067/s0717-95022017000300004.

[29] T. Bishop and R. Karne, "A survey of middleware," in *Proc. 18th Int. Conf. Comput. Their Appl.* Honolulu, HI, USA, Mar. 2003, pp. 254–258. [Online]. Available: http://triton.towson.edu/~karne/research/middlew/surveym.pdf

[30] M. Quigley et al. *ROS: An Open-Source Robot Operating System*. Accessed: Oct. 20, 2022. [Online]. Available: http://stair.stanford.edu

[31] V. Palomino-Díaz and P. Romero-Sorozábal, *Diseño Conceptual De Una Plataforma Robótica Para Ayudar A Que Los Niños Con Parálisis Cerebral Descubran Cómo Caminar*. burjcdigital.urjc.es. Accessed: Nov. 4, 2022. [Online]. Available: https://burjcdigital.urjc.es/bitstream/handle/10115/17868/Actas_V2%281%29.pdf?sequence=3&isAllowed=y#page=84

[32] S. L. Lara, M. D. del Castillo, J. I. Serrano, E. Rocón, R. Raya, and I. M. Caballero, "EEG control of gait in children with cerebral palsy. Preliminary data for the construction of a brain computer interface," *Gait Posture*, vol. 42, p. S42, Sep. 2015, doi: 10.1016/j.gaitpost.2015.06.082.

[33] P. Sorozabal, G. Delgado-Oleas, Á. Gutiérrez, and E. Rocon, "Generador de patrones de marcha tridimensionales dependientes de la velocidad para el control de exoesqueletos," in *Proc. 43rd Jornadas Automática Libr. Actas 7, 8 Y 9 Septiembre*, Logroño, Spain, Sep. 2022, pp. 128–133, doi: 10.17979/SPUDC.9788497498418.0128.

[34] S. Shalunov, B. Teitelbaum, A. Karp, and J. Boote. (2006). *A One-Way Active Measurement Protocol (OWAMP)*. Accessed: May 17, 2023. [Online]. Available: https://www.rfc-editor.org/rfc/rfc4656.html

[35] D. L. Mills, "Internet time synchronization: The network time protocol," *IEEE Trans. Commun.*, vol. 39, no. 10, pp. 1482–1493, Oct. 1991, doi: 10.1109/26.103043.

[36] D. M. Navarro, P. Copaci, D. A. Guadalupe, and J. Blanco, "Desarrollo de un exotraje basado en SMA para pacientes pediatricos," *Jornadas Robótica y Bioingeniería*, pp. 251–258, Jul. 2023, doi: 10.20868/UPM.book.74896.

[37] H. Kawamoto, T. Hayashi, T. Sakurai, K. Eguchi, and Y. Sankai, "Development of single leg version of HAL for hemiplegia," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Sep. 2009, pp. 5038–5043, doi: 10.1109/IEMBS.2009.5333698.

[38] J. A. Blaya and H. Herr, "Adaptive control of a variable-impedance ankle-foot orthosis to assist drop-foot gait," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 12, no. 1, pp. 24–31, Mar. 2004, doi: 10.1109/TNSRE.2003.823266.

[39] J. E. Pratt, B. T. Krupp, C. J. Morse, and S. H. Collins, "The RoboKnee: An exoskeleton for enhancing strength and endurance during walking," in *Proc. IEEE Int. Conf. Robot. Autom.*, vol. 3, May 2004, pp. 2430–2435, doi: 10.1109/robot.2004.1307425.

[40] S. Wang, C. Meijneke, and H. van der Kooij, "Modeling, design, and optimization of mindwalker series elastic joint," in *Proc. IEEE 13th Int. Conf. Rehabil. Robot. (ICORR)*, Jun. 2013, pp. 1–8, doi: 10.1109/ICORR.2013.6650381.

[41] C. A. Laubscher, R. J. Farris, and J. T. Sawicki, "Design and preliminary evaluation of a powered pediatric lower limb orthosis," in *Proc. ASME Des. Eng. Tech. Conf.*, 2017, pp. 1–9, doi: 10.1115/DETC2017-67599.

[42] C. Bayón, O. Ramírez, M. D. Del Castillo, J. I. Serrano, R. Raya, J. M. Belda-Lois, R. Poveda, F. Mollà, T. Martín, I. Martínez, S. L. Lara, and E. Rocon, "CPWalker: Robotic platform for gait rehabilitation in patients with cerebral palsy," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2016, pp. 3736–3741, doi: 10.1109/ICRA.2016.7487561.

[43] Z. F. Lerner, D. L. Damiano, and T. C. Bulea, "A lower-extremity exoskeleton improves knee extension in children with crouch gait from cerebral palsy," *Sci. Transl. Med.*, vol. 9, no. 404, Aug. 2017, Art. no. eaam9145, doi: 10.1126/SCITRANSLMED.AAM9145/SUPPL_FILE/AAM9145_TABLE_S2.ZIP.

[44] M. A. H. M. Adib, "Restoration of kids leg function using exoskeleton robotic leg (ExRoLEG) device," in *Proc. 10th Nat. Tech. Seminar Underwater Syst. Technol.*, vol. 538, 2019, pp. 335–342, doi: 10.1007/978-981-13-3708-6_28.

[45] C. Meijneke, G. van Oort, V. Sluiter, E. van Asseldonk, N. L. Tagliamonte, F. Tamburella, I. Pisotta, M. Masciullo, M. Arquilla, M. Molinari, A. R. Wu, F. Dzeladini, A. J. Ijspeert, and H. van der Kooij, "Symbitron exoskeleton: Design, control, and evaluation of a modular exoskeleton for incomplete and complete spinal cord injured individuals," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 29, pp. 330–339, 2021, doi: 10.1109/TNSRE.2021.3049960.

[46] L. J. A. Mayag, M. Múnera, and C. A. Cifuentes, "Human-in-the-loop control for AGoRA unilateral lower-limb exoskeleton," *J. Intell. Robotic Syst.*, vol. 104, no. 1, p. 3, Jan. 2022, doi: 10.1007/s10846-021-01487-y.

[47] C. Akkawutvanich and P. Manoonpong, "Personalized symmetrical and asymmetrical gait generation of a lower-limb exoskeleton," *IEEE Trans. Ind. Informat.*, vol. 19, no. 9, pp. 9798–9808, Sep. 2023, doi: 10.1109/TII.2023.3234619.

[48] M. Bortole, A. Venkatakrishnan, F. Zhu, J. C. Moreno, G. E. Francisco, J. L. Pons, and J. L. Contreras-Vidal, "The H2 robotic exoskeleton for gait rehabilitation after stroke: Early findings from a clinical study," *J. NeuroEng. Rehabil.*, vol. 12, no. 1, pp. 1–12, Dec. 2015, doi: 10.1186/s12984-015-0048-y.

[49] J. Meuleman, E. van Asseldonk, G. van Oort, H. Rietman, and H. van der Kooij, "LOPES II—Design and evaluation of an admittance controlled gait training robot with shadow-leg approach," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 24, no. 3, pp. 352–363, Mar. 2016, doi: 10.1109/TNSRE.2015.2511448.

[50] F. Patané, S. Rossi, F. Del Sette, J. Taborri, and P. Cappa, "WAKE-up exoskeleton to assist children with cerebral palsy: Design and preliminary evaluation in level walking," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 7, pp. 906–916, Jul. 2017, doi: 10.1109/TNSRE.2017.2651404.

[51] D. Sanz-Merodio, J. Sancho, and M. P. Erez, "Control architecture of the ATLAS 2020 lower-limb active orthosis," in *Proc. Adv. Cooperat. Robot.*, 2020, pp. 860–868.

[52] D. Eguren, M. Cestari, T. P. Luu, A. Kilicarslan, A. Steele, and J. L. Contreras-Vidal, "Design of a customizable, modular pediatric exoskeleton for rehabilitation and mobility," in *Proc. IEEE Int. Conf. Syst., Man Cybern. (SMC)*, Oct. 2019, pp. 2411–2416, doi: 10.1109/SMC.2019.8914629.

[53] J. Chen, J. Hochstein, C. Kim, L. Tucker, L. E. Hammel, D. L. Damiano, and T. C. Bulea, "A pediatric knee exoskeleton with real-time adaptive control for overground walking in ambulatory individuals with cerebral palsy," *Frontiers Robot. AI*, vol. 8, pp. 1–16, Jun. 2021, doi: 10.3389/frobt.2021.702137.

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