Development and Design of an Innovative Smart Exoskeleton-Crutch System

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Abstract: *This paper presents the development of the DEXO-1, a novel lower limb exoskeleton designed to assist gait and rehabilitation of the musculoskeletal system. The exoskeleton provides six degrees of freedom for each leg. This includes four active degrees of freedom at the hip and knee joints, along with two passive degrees of freedom at the ankle joints. The paper details the modeling and control process, The system's design and sensor system are also described, along with using instrumented crutches as part of the human-machine interface (HMI) and for maintaining balance. Furthermore, it is explained how the exoskeleton and crutches are equipped with force sensors to capture ground reaction forces, which are used in the intuitive and user-friendly HMI. This HMI generates motion patterns based on interaction forces with the ground and is based on the user's trunk motion and the use of buttons. From modeling, the control scheme, and the human-machine interface, it is expected that DEXO-1 will provide a promising solution for lower limb gait assistance and musculoskeletal rehabilitation. Its design, sensor system, and user-friendly HMI will offer users a more natural and responsive interface.*

Keywords *Lower-limb exoskeletons, disability, mobility, rehabilitation.*

1. Introduction

The Brazilian Institute of Geography and Statistics (IBGE) recently conducted a survey as part of the 2019 National Health Survey (PNS) in partnership with the Ministry of Health. The results of the survey revealed that 17.3 million people in Brazil, or 8.4% of the population over 2 years old, have some type of disability. Of this group, 49.4% are elderly. The survey also found that 7.8 million people, or 3.8% of the population over two years old, have a physical disability in the lower limbs [3]. This highlights the need for innovative solutions to address mobility issues, such as lower-limb exoskeletons, which can help individuals with lower-limb disabilities to walk and perform daily activities with increased ease and independence. The survey also showed that the majority of people with disabilities, 10.5 million, are women, which further underscores the importance of developing and providing accessible and effective solutions for this population.

Lower-limb exoskeletons have emerged as a promising technology for enhancing the mobility and independence of individuals with lower-limb disabilities. These devices consist of wearable robotic components that are attached to the legs and hips, providing support and assistance for walking, climbing stairs, and performing daily activities. The development of lower-limb exoskeletons has been driven by the increasing demand for rehabilitation and assistive devices for individuals with disabilities and the aging population.

In recent years, there has been a growing body of research on lower-limb exoskeletons, and a number of important papers have been published in this area. These papers have focused on various aspects of exoskeleton design, control, and functionality, and have provided valuable insights into the *current state of the art in this field. In this paper, we present the results obtained by developing a lower limb exoskeleton assisted using Canadian crutches and their interface.*

The exoskeleton development project has been divided into several stages for increased flexibility and improved risk management. To commence, a CAD design of the exoskeleton was created, followed by the dynamic analysis of the system using the CAD model in the CoppeliaSim robotics simulator. The subsequent stage involved the construction of the actual exoskeleton equipped with high-torque continuous current motors and integrated smart crutches that also served as part of the Human-Machine Interface (HMI). Further development will involve the implementation of a laser-pointing technique to optimize trajectory and step placement. Lastly, augmented reality glasses will be utilized to enhance the user experience and a depth sensor was integrated to map the environment.

The manuscript is organized as follows; in section 2, we describe the types of exoskeletons classified by their applications and their characteristics; in section 3, our proposal for the control scheme, the HMI, and the electro-mechanical exoskeletal framework.

2. State of the Art

The early research on lower limb rehabilitation exoskeleton robots dates back to the 1960s. Professor M. Vukobratovic and his colleagues developed a pneumatically-driven walking exoskeleton in 1969 [2]. Around the same period, General Electric launched a project led by Ralph Mosher, known as Hardiman, which was a prototype full-body exoskeleton with a 680 kg payload and hydraulic pumps. Mosher had previously worked on the original Handyman design, a remotely-controlled hydraulic arm. Exoskeletons can be classified based on their actuator, control, or level of assistance, such as lower limbs, upper limbs, whole body, etc. The three main categories of lower limb exoskeletons explored in this paper are: assistive exoskeletons, rehabilitation exoskeletons, and ability-enhancing exoskeletons [7].

Assistive exoskeletons aim to restore the wearer's ability to perform daily activities for individuals with conditions such as strokes, spinal cord injuries, or muscle weakness. Most of these exoskeletons are powered by DC motors, and recent advancements in technology have made electric motors more powerful and efficient, while battery improvements have increased their power density while maintaining safety. Typically, a predefined joint trajectory is used, requiring precise control.

Rehabilitation exoskeletons are designed to help patients regain their motor functions to the point where they can live without assistance after the rehabilitation phase. These exoskeletons require real-time system monitoring and feedback signals to accurately estimate the level of support required. They also make the therapist's job easier by moving the limbs using the exoskeleton, rather than manual handling. For individuals with complete lower extremity paralysis or weakness due to spinal cord injury (SCI), stroke, or other neurological deficits, exoskeletons can improve gait or restore lost movement abilities, thereby aiding or replacing the lower extremity's support and gait functions.

Ability-enhancing exoskeletons are worn by individuals without any disabilities, and are designed to provide superior human-like abilities, such as increased strength, faster walking/running speed, enhanced carrying capacity, or longer distances covered. Predefined trajectories are not necessary, but the control system needs to follow the user's limb movement using admittance/impedance controls and sensitivity amplification control. Series elastic actuators (SEA) and pneumatic actuators are commonly used in this type of exoskeleton.

This paper focuses on assistive exoskeletons and their human-machine interface. These exoskeletons offer complete autonomy as they are not attached to any other structure or machine, and they do not require real-time limb monitoring like rehabilitation devices. Ability-enhancing exoskeletons, on the other hand, require higher budgets due to the need for stronger building materials, as the *actuators need to apply higher forces while maintaining a low weight.*

Our state-of-the-art exoskeleton excels in multiple aspects. It offers a portable design ideal for extended use. Enhanced affordability is achieved through cost-effective materials. Adaptive control algorithms discern user movement intentions, optimizing exoskeleton support—integrated sensors, including inertial measurement sensor (IMU) , force sensors, improved control, and Intuitive user interfaces simplify interaction. In the followings section we discus the control scheme, Human-Exoskeleton interface and electro-mechanical structure.

3. Results

3.1 Control Scheme

Figure 1 shows the overall control scheme of the exoskeleton. This algorithm computes critical gait parameters by considering parameters such as the terrain type (level ground, ramps, stairs, or unstructured terrain), the exoskeleton's current state, and its inherent stability.

For the modeling of the lower exoskeleton, we initially referred to the methodologies outlined in [6] by Tedrake, specifically in Appendix B1 and B2. Due to space constraints, the detailed model description from the aforementioned source has been omitted. However, interested readers can find a comprehensive treatment of underactuated systems and their control algorithms in the provided reference .

Before operation, the user selects the desired gait type from options such as level ground, ramps, stairs, and unstructured terrain. The exoskeleton's current state is described by the vector $\mathbf{q} = [\theta_1, \theta_2, \theta_3, \theta_4, \theta_5]$ *which represents the angle of each joint and torso orientation.*
In conjunction with these aspects, stability is maintained by calculating the gait parameters. This ensures that trajectories are generated to prevent the center of gravity (CoG) projection onto the ground from approaching or surpassing the support polygon's periphery. This prevention is essential to avoid instability [5], and it's achieved by measuring the center of pressure (CoP). This computation takes into consideration the spatial coordinates of ground contact points in three-dimensional space, coupled with pressure distribution across these points. We employ the Realsense D435i depth sensor from Intel, USA, to determine the crutch position. Notably, this depth sensor serves as a means to determine the crutches' spatial position; on the other hand, the crutch orientation is determined by an IMU mounted in each crutch. Moreover, our exploration extends to leveraging the depth sensor's capabilities beyond crutch position determination. In particular, we are investigating its potential to map the environment situated in front of the system. This endeavor promises to generate adaptable gait patterns suitable for traversing unstructured environments. Additionally, the orientation of the

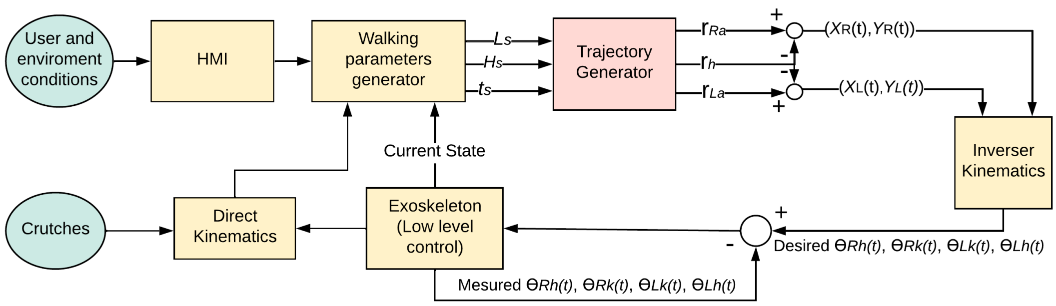

Figure 1. Exoskeleton control diagram.

trunk is considered when creating precise trajectories that accommodate the user's posture. This orientation is derived from an IMU placed in the exoskeleton's trunk.

Subsequently, these calculated gait parameters serve as inputs for the trajectory generator component. These parameters encompass step length (L_S), maximum separation between the foot and ground (H_S), and the execution time (T_S). The trajectory generator creates a discrete representation, generating positions in the sagittal plane for the right ankle (r_{Ra}), left ankle (r_{La}), and hip (r_h). This representation is achieved through the discretization of trajectories into fifty points.

Following this, the trajectory data is converted into joint angles, which then dictates the behavior of the four motors ($\theta_{Rh_{(t)}}$, $\theta_{Rk_{(t)}}$, $\theta_{Lh_{(t)}}$, and $\theta_{Lk_{(t)}}$). This transformation relies on inverse kinematic equations. Finally, the high-level controller is in charge of transmitting pairs of joint angles and velocities to each motor. Each motor's driver is equipped with a low-level PI control system, effectively controlling the desired joint angles.

3.2 Human-Exoskeleton Interface

The Finite State Machine (FSM) illustrated in Fig. 2 describes the interface structure which consists of nine states, denoted by S_1 through S_9. The half-step swings, represented by S_3 and S_7, are dependent on the state of the stop flag f_s, which has a value of zero for gait initiation and one for gait termination. During the gait initiation cycle, the swing motion moves one foot ahead of the other. Conversely, in the gait termination cycle, the swing motion brings the feet together at the same distance from the frontal plane. Note that the swing motion is performed differently depending on the state of f_s.

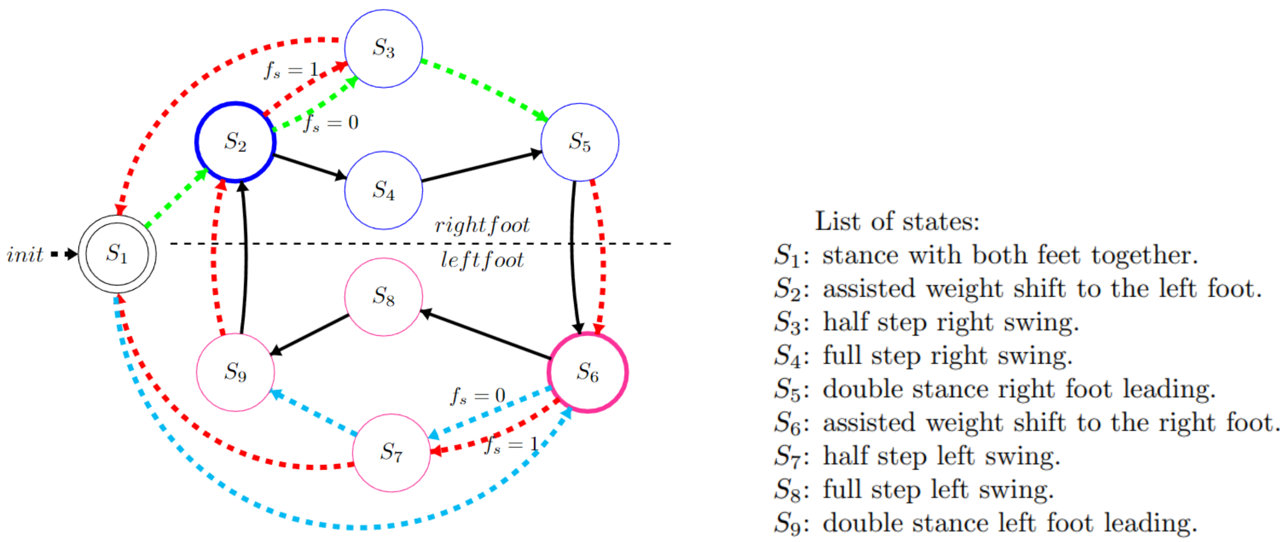

Figure 2. Exoskeleton´s interface FSM for walking. Gait initiation in green dashed arrows and cyan dashed arrows, for starting with right and left foot swings respectively. Blue and magenta colored nodes represent the right and left foot swing phases respectively. Full gait cycle in black solid arrows. Gait termination in dashed red arrows.

Based on previous research involving trans-radial upper limb prosthesis interfaces [1] we proposed the use of a multimodal and multichannel Human Machine Interface (HMI) for an exoskeleton. Additionally, the use of crutches serves a dual purpose of assisting patients in maintaining balance while also serving as part of the control system and user interface for the exoskeleton (see Figure 3). The crutch handle is equipped with a panel of buttons that enable state machine transitions, allowing *the exoskeleton to switch between different gait modes such as sitting and standing from a chair. Each crutch includes an IMU that precisely measures acceleration and angular velocity on all three axes.*

Finally, the force sensor measures ground reaction force and provides data for calculating the exoskeleton's CoP. The trajectory generator algorithm takes the before mention information to create the angle trajectories for each joint.

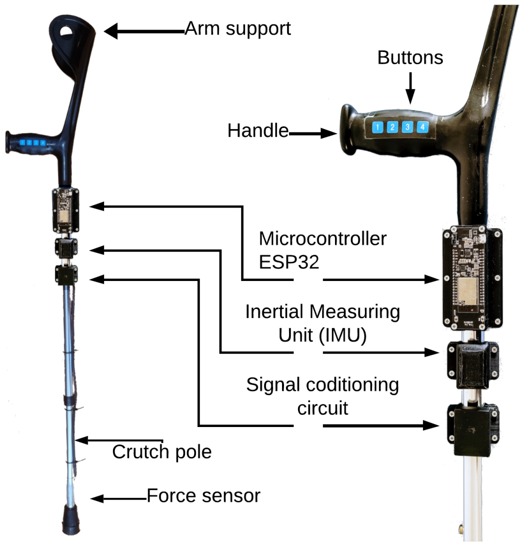

Figure 3. Side view of right exoskeleton smart crutch prototype

3.3 Electro-Mechanical structure

The exoskeleton is designed with 6 DoF (Degrees of Freedom), 4 of which are actuated. Two DoFs in each leg, one for the hip flexion/extension and another one for knee flexion/extension. We've chosen to design our lower limb exoskeleton with only four actuators. This decision optimizes weight, simplifies construction, and reduces costs. Since users utilize crutches for balance, maximal actuator torque in all joints isn't essential. Our analysis shows that static walking can still be achieved without actuation in certain joints, highlighting the effectiveness of our design approach.

The exoskeleton prototype and user in Figure 4, are equipped with 4 BLDC motors (My Actuator, China). Each motor is coupled with internal planetary gears and hall sensors at the input and output, which are used to indicate position. The hips and knees are powered by a 50 N.m RMD-X10 motor and a 35 N.m RMD-X8 Pro motor, respectively. The manufacturer seamlessly integrates each motor's driver within the motor assembly. This built-in driver can handle peak currents of up to 50A, and two cascade PI controllers are employed as low-level controllers for each motor, using position, velocity, and torque feedback. Additionally, the design incorporates two passive degrees of freedom at the ankles, achieved through the use of spring elements. Although these passive joints do not offer direct control, they enable compliance with the ground and improved traction by integrating rubber soles. The ankle joints are fitted with Hall effect sensors to measure the joint angle precisely.

Figure 4. Front view of exoskeleton prototype and user

4. Conclusion

The methodology for the development and design of an innovative smart exoskeleton-crutch system was presented, aimed at addressing the mobility issues of individuals with lower-limb disabilities. The paper discussed the current state-of-the-art lower-limb exoskeleton research and highlighted the importance of developing accessible and effective solutions for this population. The objectives outlined in the introduction, covering aspects of modeling, control, human-machine interface, and smart crutches, have been accomplished through the application of the methods described in this paper. The methods encompassed the modeling of the exoskeleton, the control scheme, and the human-machine interface. The results demonstrate the potential for the proposed exoskeleton-crutch system to provide support and assistance for individuals with lower-limb disabilities, helping them to walk and perform daily activities with increased ease and independence.

In future work, we plan to integrate optical-fiber-based force myography sensors [4] onto the user's lower-limb main groups of muscles to obtain the user intent, thus creating a semi-transparent interface for rehabilitation, instead of using EMG sensors as they tend to have cumbersome results out of clinic environments.

Acknowledgement

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