HOPE-G: A new design for gait rehabilitation robotic structure

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Abstract. *This research focuses on the development of the two mechanical models of HOPE-G, a gait rehabilitation robot. It describes the methodological approaches for dimensioning pneumatic actuation systems and the parallel manipulator in the body weight support. Simulation results show that the operating point method balances energy efficiency and dynamic performance. Additionally, experimental tests with healthy volunteers confirm the mobility and potential effectiveness of the integrated system for gait training with a serious game. Finally, the preliminary results highlight the potential benefits of the novel structure in rehabilitation processes.*

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1. Introduction

Stroke, characterized by the loss of neurological functions due to interrupted blood flow in the brain, necessitates effective rehabilitation strategies to restore motor abilities [Salvadori et al. 2020, Gonçalves and Rodrigues 2022]. Robotic tools have gained recognition as valuable assets in the rehabilitation process, offering benefits such as cost reduction and expanded exercise options [Artemiadis and Krebs 2011]. Specifically, body weight-supported treadmill training has emerged as a prominent approach, involving the use of body weight support (BWS) harnesses and robotic assistance to aid patients in gait rehabilitation [Artemiadis and Krebs 2011].

Various robotic structures have been developed to automate and enhance the BWS-supported gait rehabilitation process. These structures include exoskeletons, orthoses, and rehabilitation treadmill systems. For example, the LOPES exoskeleton [Veneman et al. 2007] provides active BWS and assists in pelvic translation, while the robotic gait rehabilitation (RGR) [Pietrusinski et al. 2010] system focuses on treating gait in post-stroke patients through a connected orthosis. The Lokomat orthosis combines BWS and a treadmill for lower limb rehabilitation, with optional pelvis translation and rotation capabilities [Rodrigues and Gonçalves 2023].

While BWS systems show promise for gait rehabilitation, challenges remain in optimizing their design and assessing their benefits accurately. The static nature of many BWS devices limits adaptability to changes in trunk height, and their influence on pelvis and thorax movements during gait remains a topic of study. Furthermore, there is a need to explore alternative actuation systems for rehabilitation equipment to address safety concerns and improve performance [Swinnen et al. 2015, Hesse et al. 2003].

This paper presents a novel approach to address the challenges in gait rehabilitation by combining two key elements: a robotic structure and the utilization of servopneumatic systems for position control. The robotic structure is designed to withstand patients' passive weight and enable controlled actions without relying on high-power actuators. It incorporates an active BWS system that facilitates translations and rotations in the frontal and transverse planes while restricting the sagittal plane. The servopneumatic systems offer compliance and shock absorption, addressing safety concerns and enabling natural movement patterns akin to human muscle contraction. The conceptual representation of this structure is presented in Figure 1.

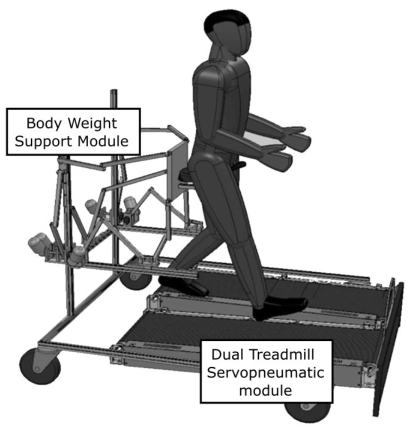

Figure 1. Conceptual Design of the HOPE-G structure, highlighting the modules that compose the system.

Through this integrated approach, the paper contributes to the advancement of robotic rehabilitation tools and techniques. The proposed combination of an innovative robotic structure with active BWS and servopneumatic actuators holds significant potential for enhancing gait rehabilitation outcomes. The results and discussions presented in this paper shed light on the effectiveness, safety, and adaptability of the proposed structures. By improving the understanding of these technologies, this research paves the way for future developments in personalized and technology-driven neurorehabilitation approaches.

2. Mathematical models

2.1. BWS inverse geometric model

The proposed design of the BWS structure aims to minimize the coupling of joint coordinates by employing a specialized architecture known as the "multipteron" family [Gosselin et al. 2015]. This architecture focuses on restricting the pelvis's sagittal movement since it has a low influence on the rehabilitation process of human gait. The proposed structure consists of a 4-PRRU + PRRS configuration, as shown in Figure 2(a). Here, P denotes an actuated prismatic joint, R represents a rotational joint, U signifies a universal joint, and S indicates a spherical joint. Point P on the mobile platform serves as the location for the patient's seat.

In Figure 2(a), translational and rotational joints are depicted as cylindrical joints (q_i, i = 1 to 5) for simplicity, although both translation and rotation joints are utilized in the prototype's construction. Universal joints are represented as cross-cylinders, and the spherical joint is illustrated as a dashed circumference positioned behind the mobile platform.

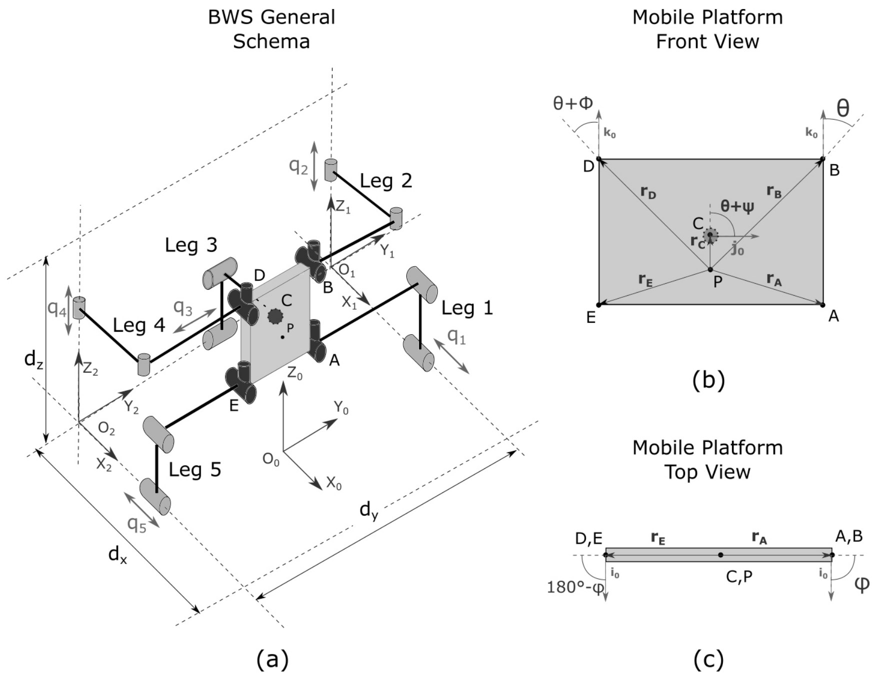

Figure 2. (a) Diagram of joints and references of the (4-PRRU+PRRS) structure; Details of the point of interest and reference angles in the (b) front view; and (c) top view of the mobile platform.

The modeling of this system employs equipollent coordinates for the references shown in Figure 2(a), ensuring that each joint coordinate (q_i) aligns with one of the unit vectors in the reference frame. Consequently, for each leg (i), the vector (u_i) connecting the active joint of that leg to a point on the mobile platform belonging to a plane perpendicular to the actuator's unit vector direction is highlighted. Using these considerations, the structure's modeling is conducted by analyzing each leg individually and consolidating the obtained equations into a matrix that relates to the joint and operational coordinates [Rodrigues and Gonçalves 2023].

To examine the position of point A on the mobile platform concerning a specific leg (i) about the inertial reference, it can be equated with the position relative to the leg's references. For instance, for Leg 1, this relationship is illustrated in Figure 3 and formalized in Equation (1):

$$^0r_p + r_A = ^0r_1 + q_1 i_1 + u_1 \tag{1}$$

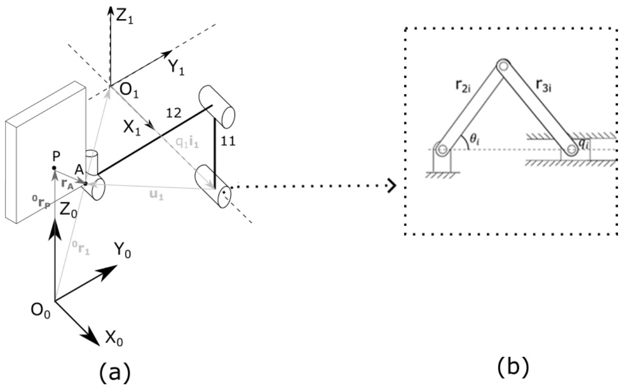

Figure 3. (a)Vector analysis of the position of point A in relation to the inertial frame and leg 1; (b) Adaptation of a 3-bar crank-rod mechanism to the linear actuators q_i.

Here, r_p represents the position of point P with respect to the $X_0Y_0Z_0$ reference frame, r_A is the relative position of point A concerning point P, and i_1 denotes the unit vector in the X direction of the reference frame $X_1Y_1Z_1$. The vector u_1 lies within a plane parallel to the Y_1Z_1 plane, perpendicular to the unit vector i_1, where i_1 = i_0 due to the adoption of references with equipollent coordinates. By performing a dot product on both sides of Equation 1 with i_0, the angle φ, illustrated in Figure 2(c), is obtained, representing the orientation of the mobile platform in terms of its rotation around the Z_0 axis.

Similar procedures are applied to legs 2 to 5 their respective equations, following the same principle. Taking the time derivatives of these equations, it is possible to obtain the consolidated matrix form $[J_q]\{\dot{q}\} = [J_x]\{\dot{x}\}$, and calculate the determinant of $[J_x]$ to perform a singularity analysis. As per the analysis performed, no feasible singular position inside the workspace of the structure was found [Rodrigues 2022].

In summary, the mathematical model of the BWS structure incorporates the multipteron architecture and equipollent coordinates to capture the joint and operational coordinates. By ensuring the avoidance of singular positions and utilizing an efficient actuator model, the design aims to optimize the rehabilitation process and enable smooth and controlled movements during gait training. Further details of the mathematical model of the BWS are described in [Rodrigues 2022].

2.2. Servopneumatic Dual Treadmill model

The active gait movement module of HOPE-G comprises a bipartite treadmill that enables natural human leg gait with one degree of freedom [Rodrigues 2022]. Each leg is stimulated by one of the treadmills, as depicted in Figure 4(a). To determine the dimensions of the pneumatic actuators, a free-body diagram of the system is illustrated in Figures 4(b) and 4(c).

In this subsection, we discuss the key requirements for sizing the actuators in this module [Vigolo et al. 2022]. These requirements include the system mass (M), total cylinder stroke (L), desired displacement time (t_d), and load force (F_C). The system mass is the sum of the treadmill mass (26 Kg) and the patient's mass (limited to 150 Kg), resulting in a total mass of 176 Kg. The displacement time refers to the time taken to

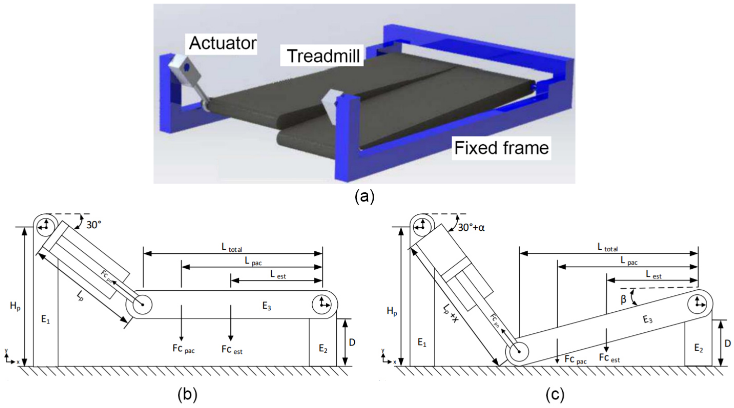

Figure 4. (a) Conceptual image of the dual treadmill module; Free-body diagram of the treadmill: (b) horizontal position; (c) drop position.

move the treadmill from its horizontal position to its low position, and a time of 2 seconds is assumed for a complete movement.

The total cylinder stroke is determined by the maximum vertical displacement of the treadmill (D), considering the angular displacement due to the actuator joint. Assuming a 30^o angle with the horizontal for the horizontal position of the treadmill and a vertical displacement of 0.0762 m, the actuator stroke must be at least 0.1 m. The load force is determined based on the static force, calculated by summing the moments acting on mechanism link 3. The maximum static force is 1,726.5 N, which occurs when the treadmill is in the horizontal position.

The sizing procedure for the pneumatic cylinders involves the determination of diameter specifications using three distinct methods. These methods are the classical method, which considers the hydrostatic relationship between fluid pressure and area; the natural frequency method, which accounts for the natural frequency of the actuator; and the operating point method, which analyzes the steady-state behavior of the actuation system. Equations for each method can be found in [Vigolo et al. 2022]. The calculated diameters, approximated to commercial values, are presented in Table 1, considering the supply pressure correction based on the selected commercial actuator area.

Table 1. Actuation Components Specification

Sizing method	Calculated Diameter[m]	Catalog diameter [m]	Supply Pressure [Pa]	Area Ratio
Classical	0.07045	0.063	8.3×10^5	0.8992
Natural frequency	0.03874	0.040	7.1×10^5	0.8400
Operating point	0.07805	0.080	6.8×10^5	0.9023

3. Computational Simulations of the systems

3.1. BWS simulation and optimization

A computational model was developed to determine the dimensions of mechanical elements and actuators in the body weight support (BWS) system, considering geometric and dynamic characteristics. The model accounted for the patient's mass as a dynamic load transmitted to the DC motors through a connecting crank-rod mechanism. Certain mechanical elements' mass and inertia were disregarded due to the low speeds and accelerations involved in human gait rehabilitation. The simulation details and algorithms can be found in [Rodrigues 2022].

The dynamic model calculations took into account various criteria. Linear guides are needed to withstand the maximum static load and traverse the specified workspace within a critical cycle time. Bars connecting the linear guides to the DC motors were required to support the maximum dynamic load without considering inertia. Actuators 2 and 4 were equipped with passive spring systems to alleviate the static load, while an additional spring was connected to the mobile platform for enhanced passive support and load relief of other actuators, Fig. 5.

The dynamic equation determined the maximum effort applied to each actuator based on parameters such as the working space of linear guides (d_i) and the critical cycle time (t_c). Correction factors (f_r) were applied to consider weight distribution among different actuators. The model also incorporated minimum requirements for electrical power and angular speed of the DC motors to ensure proper movement of the connecting crank-rod mechanism.

Optimal dimensions for the bars and the necessary characteristics for the DC motors were obtained using a computational model implemented in MATLAB®. The model utilized a differential evolution algorithm and considered parameters such as the number of replications, population size, maximum iterations, crossover rate, and mutation probability. The results provided the optimal dimensions for the bars and the specifications for the DC motors.

After running the algorithm, the optimal dimensions were obtained, being 250 mm for bars r_{2i} and 300 mm for bars r_{3i},r_{4i}, and r_{5i}, Fig. 3. Regarding the power and speed requirements, results present that a DC motor with 35 W and 20 RPM nominal angular velocity will be enough for the structure requirements.

3.2. Servopneumatic system simulation and controller design

The analysis of the sized actuators involved a dynamic simulation model consisting of a linear actuator and a servo valve. The model accurately represented the system's behavior by considering factors such as mass flow, pressure, temperature, motion, and friction. The implementation of this nonlinear model in MATLAB/Simulink® was thoroughly described in [Vigolo 2018, Vigolo et al. 2020].

To achieve closed-loop control, an impedance control strategy was employed, which simultaneously controlled force and position. This control approach utilized a reference mass-spring-damper system to establish the force-position relationship. It should be noted that the impedance control generated a force reference signal, which was transformed into a voltage value for the proportional valve through the force control system.

The force control system utilized a conventional PID control method to track the desired force trajectory. By comparing the desired force with the actual pneumatic force produced by the actuator, the control system generated an error signal that guided the control action. This approach proved effective in most cases, although adaptive gains in the PID controller could improve the control system's ability to follow the desired trajectory.

The simulation results demonstrated the performance of three different actuators with varying diameters. The diameters considered were obtained using the classical method (63 mm), the operating point method (80 mm), and an oversizing case (100 mm). All three actuators successfully tracked the reference signal, but during direction changes, they exhibited higher errors, potentially due to the accumulation of air in one of the chambers. Additionally, the results showed that the 63 mm actuator consumed the least compressed air, while the 100 mm actuator consumed the most, being 125% higher than the 68 mm cylinder. The 80 mm actuator demonstrated an intermediate level of compressed air consumption, approximately 34% higher than the smallest actuator.

4. Experimental tests

4.1. Prototype building and control requirement analysis

The first prototype of the structure was built as shown in Figure 5. The system features a saddle-shaped seat that provides comfortable support based on studies highlighting its effectiveness in distributing the patient's weight [Gonçalves and Krebs 2017]. The seat is firmly fixed on a mobile platform, and additional overhead body-weight support can be used for added safety if necessary. The motor module comprises a crank-rod mechanism, a DC motor, an incremental encoder, a linear rail, and an end-of-course switch. The leg of the device consists of links, revolute joints, and a coupling joint on the mobile platform.

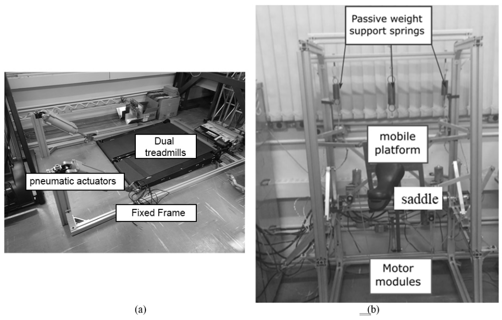

Figure 5. First prototype of HOPE-G: (a) Dual treadmill module; (b) BWS.

The actuation components used in the prototype are low-cost and readily available in the laboratory. Each actuator is controlled using a PID-type position controller and an "Assist-As-Needed" (AAN) function [Asl et al. 2019]. The PID controller is fine-tuned using a meta-heuristic optimization system based on a differential evolution algorithm [Gonçalves et al. 2016]. The AAN function dynamically suppresses the PID action and applies it only when needed by the patient.

Experimental tests were conducted to verify the effectiveness of the differential evolution algorithm in obtaining the necessary constants for the PID controller. The collected data from the tests were analyzed using Python and Jupyter Notebooks, and the results indicated consistent compliance with the specified settling time, demonstrating an appropriate system response [Rodrigues and Gonçalves 2023].

Based on the experimental results, it can be concluded that the designed structure is suitable for practical tests with healthy patients, as it met the desired requirements and exhibited reliable performance. Further investigation is necessary to address and eliminate the remaining stationary error and improve the system in future iterations.

4.2. First trials of the structure

The experimental trials conducted at the Federal University of Uberlândia received ethical approval from the human research ethics committee (CAAE 01305318.2.0000.5152). The tests involved the utilization of a newly proposed body weight support system, combined with a developed serious game. Prior to participation, all individuals provided informed consent.

The trial included two healthy volunteers, one male and one female, both aged 18 or above. The objectives of the trial encompassed several aspects: assessing the functionality of the structure and treadmill during human gait; evaluating the control of the main character in the game while executing the human gait; analyzing gameplay and difficulty levels during actual usage; and identifying any electrical or mechanical malfunctions during operation. Two test sessions, each lasting approximately 5 minutes, were conducted. Figure 6 displays a photograph from one of the test sessions.

Figure 6. Picture taken during a test session with a healthy participant.

To commence the trial, the neutral position of the platform was adjusted based on the height of each participant. Subsequently, the participants were positioned on the structure, and the treadmill was activated. Initially, the participants walked on the treadmill without the game running to verify the appropriateness of the speed and comfort level provided by the platform.

Once the initial conditions were confirmed with the participants, the game was initiated, and the test session was recorded via video. Upon completion of the session, the recordings were stopped, and the volunteers shared their primary impressions of both the structure and the serious game.

One noteworthy feedback provided by the participants pertained to the execution of gait on the treadmill with the platform. Both individuals reported being able to walk naturally, with minimal to no impact from the saddle on their movements. During the game, participants encountered slight difficulties in maneuvering the character, particularly while moving left or right on the treadmill, primarily due to limited lateral space. Additionally, when the platform inclined in the game, the participants noticed the displacement, requiring them to adapt their gait movements accordingly.

The video footage of the experimental tests and the computational simulations presented in this paper can be accessed in:
https://drive.google.com/drive/folders/17bZKsnUAPb1jSSVaHco1ahpjLiTBqhZM

5. Conclusions

This paper presents the design and functionality of an innovative active gait rehabilitation robotic system, divided into two robotic modules, as its primary contribution. The BWS module adopts a parallel structure with minimal coupling in movements. This allows for simpler control and greater independence of actuators, despite the closed-chain configuration. Moreover, the optimization of dimensions is not limited by singular positions. The system was developed with a focus on affordability to facilitate its use in low-income countries.

The dual treadmill module applies and also innovates with the use of servopneumatic actuators. Three different methods were compared to achieve the desired design of this module. Based on the results obtained in simulations, it can be concluded that the operating point method was suitable for the case, obtaining a specification for pneumatic actuators that balance energy efficiency with maximum dynamic performance.

Experimental tests were conducted using the novel system integrated with a serious game. The tests revealed certain constructive aspects that require improvement to enhance the overall training experience. Insights from tests conducted with healthy volunteers provided recommendations for enhancing the control system of the main character, optimizing the physical structure assembly, improving actuator assembly, and making adjustments to the serious game.

In future research, it is suggested to explore the use of machine learning to obtain and evaluate trajectory profiles of healthy human gait from the telemetry of the system. This data can be utilized to control the dead zone of the assist-as-needed function based on observed deviations in the gait profile. Another potential avenue for future work involves incorporating a haptic virtual environment. The next phase of the study involves conducting clinical tests with post-stroke patients.

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