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STRUCTURAL SYNTHESIS AND DYNAMIC ANALYSIS OF A NEW HUMAN LEG MOTION ASSISTANCE MECHANISM

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Abstract: *In this paper, aspects of the structure, kinematic and dynamic analysis of a mechanism that is designed to be implemented as the leg of an exoskeleton-type robot are presented. The designed exoskeleton is intended to assist and rehabilitate human gait, and has the constructive particularity that the mechanism implemented in the leg structure is monomobile. Motion assistance is provided by assisting the hip and knee joints. Thus, through kinematic study the laws of motion in the joints of the exoskeleton, which reproduce those of the human hip and knee, are determined and a comparison is made between the laws of motion, namely the angular amplitude, realized by the exoskeleton and a healthy human subject.*

Key words: *lower limb exoskeleton, human gait, mechanical design, dynamic analysis, rehabilitation robot.*

1. INTRODUCTION

Robotic exoskeletons for lower limb rehabilitation integrate advanced technologies such as sensing and control, drawing on insights from bionics, robotics, information and control science, medicine, and other interdisciplinary domains. Because the primary objective of rehabilitation training is to help patients regain normal mobility, a thorough understanding of human gait is essential for the development of lower limb rehabilitation exoskeletons.

Rehabilitation robots, which provide direct assistance to humans, have significant potential in improving rehabilitation therapy due to the complex demands of this field. Therefore, developing advanced rehabilitation robots is essential. Research on lower limb rehabilitation robots, particularly for patients with mobility impairments, has become a major focus in this area. With an aging population and improving living standards, the number of individuals affected by limb movement disorders is rising rapidly. Such disorders can lead to abnormal gait patterns and disrupt normal walking. For patients with lower limb mobility issues, early intervention through active rehabilitation training is crucial.

The highest stroke incidence worldwide is met in China, about 15 million persons suffer from lower limb motor dysfunctions, including cerebral palsy, hemiplegia, and paraplegia. In addition, approximately 40 million older people have lost the ability to walk due to aging-related issues. Despite the pressing need for around 350,000 rehabilitation specialists, fewer than 20,000 are currently available [1]. As a result, lower limb rehabilitation robots play a vital role in addressing this gap by reducing the workload of therapists, supporting data collection during training sessions, and enabling consistent and quantitative evaluations of recovery progress [2].

Lower limb rehabilitation exoskeleton robots are a key category of rehabilitation devices designed to be worn on the body, enabling control over joint movements during training. Research in this field dates back to the 1960s [3]. Although early prototypes fell short of expectations due to technical constraints, they laid the groundwork for future advancements. In recent years, especially after the clinical

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adoption of the Lokomat system, lower limb rehabilitation exoskeleton robots have gained considerable attention in research. These devices are primarily intended to support elderly individuals and those with lower limb motor impairments by offering power assistance and aiding in the rehabilitation process.

Exoskeleton robot technology is a multidisciplinary field that merges sensing, control, information processing, and computer science to develop wearable mechanical devices. Significant progress in both theoretical and practical aspects has been achieved through the contributions of various companies and research institutions. Based on their application, these robots are classified into treadmill-based and overground systems.

Treadmill-based exoskeleton robots are designed for gait training on a treadmill, often incorporating a body weight support (BWS) system to reduce gravitational load on the legs, enhance safety, and improve balance. Notable examples include ALEX, Lokomat, and LOPES, as referenced in [4, 5]. On the other hand, overground exoskeleton robots, such as eLEGS (Exoskeleton Lower Limb Gait System), Indego, ReWalk, MINDWALKER, and HAL (Hybrid Assistive Limb), enable patients to walk on solid ground, as highlighted in [6, 7].

Exoskeleton robotic systems with single-degree-of-freedom (DOF) kinematic linkages are a key area of research and development, integrating biomechanics with technological advancements. While these systems are already effective for specific applications, ongoing innovations will be essential to improve their functionality and user adoption, potentially driving significant progress in rehabilitation and assistive technologies in the near future [8-15].

The paper is organized as follows: First, an analysis of human gait is presented. In the second section, the new design of the proposed mechanism intended for integration into an exoskeleton-type robot is introduced. Following that, a virtual prototype of the exoskeleton robotic system is developed through kinematic synthesis. This 3D model will be utilized for two primary objectives: conducting dynamic motion simulations in ADAMS View and fabricating a physical prototype using additive manufacturing techniques.

2. HUMAN GAIT ANALYSIS

Wearability is a key aspect of lower limb rehabilitation exoskeleton robots, requiring these devices to be highly compatible with the human body. As a result, a thorough understanding of lower limb anatomy and a detailed analysis of human gait are essential for the effective design and control of these robots.

Human walking is primarily driven by the coordinated movement of the lower limbs, making it necessary to study their structural and functional characteristics. Walking involves the synchronized action of the pelvis, hip, knee, and ankle, with their respective ranges of motion (ROM) outlined in Table 1 [7].

The pelvis serves as the connection between the trunk and the thighs, while the hip joint—a ball-and-socket joint formed by the femoral head and the pelvic bone—enables coordinated movement between the thighs and pelvis. This joint supports sagittal flexion/extension (fl/ex), frontal abduction/adduction (ab/ad), and transverse external/internal rotation (ext/int).

Table 1

ROM of lower limb joints.

Joint	Degree of freedom	ROM (deg)
Hip	Fl/ex angle	40/30
	Ab/ad angle	20/20
	Ext/int angle	15/15
Knee	Fl/ext angle	75/0
Ankle	Dorsiflexion/plantarflexion angle	25/35
	Ab/ad angle	10/10
	Ext/int angle	10/20

The knee is a complex joint composed of the tibiofemoral and patellofemoral joints, allowing movement in two planes. It facilitates sagittal fl/ex and transverse ext/int rotation. During walking, the knees play a key role in adjusting leg length through fl in the swing phase and maintaining fl in the stance phase to absorb shock and transfer forces through the legs.

The ankle and foot form a complex structure responsible for both shock absorption and propulsion during walking. Ankle motion primarily occurs at the talocrural and subtalar joints. The talocrural joint, located between the talus, distal tibia, and fibula, acts as a hinge joint, enabling plantarflexion and dorsiflexion. The subtalar joint, positioned between the calcaneus and talus, supports eversion/inversion and int/ext rotation.

A detailed understanding of the lower limb structure provides a solid foundation for the mechanical design of rehabilitation exoskeleton robots.

3. NEW DESIGN OF AN EXOSKELETON ROBOT

Exoskeleton robotic systems have evolved significantly in recent years, finding applications in rehabilitation, assistive technology, and industrial settings. Among the various designs, exoskeletons utilizing one degree of freedom (DOF) kinematic linkages have gained prominence due to their simplified mechanics and specific applications. One DOF kinematic linkages are characterized by their ability to allow movement in a single plane or axis, which simplifies the control algorithms and mechanical design. Common configurations include:

Series Elastic Actuators (SEAs): These linkages often incorporate SEAs that provide natural compliance and energy storage.

Pneumatic and Hydraulic Systems: Systems utilizing fluid power mechanisms to achieve smooth movements while maintaining lightweight properties.

The simplicity of one DOF systems allows for reduced weight, which is crucial for user comfort and mobility. The designs are typically used to assist specific movements, such as knee extension during walking or lifting actions in industrial applications. Exoskeletons employing one DOF kinematic linkages can be classified into various categories based on their intended use:

Rehabilitation: These systems assist patients in regaining functional movement post-injury or surgery. For instance, knee-ankle-foot orthoses (KAFOs) often employ one DOF in the knee joint to aid individuals with lower limb paralysis.

Industrial Assistance: In manufacturing and logistics, exoskeletons provide support for workers engaged in repetitive tasks, reducing strain on the lower back and legs. One DOF linkages are used in these systems to assist in lifting and carrying tasks.

Military and Mobility Aid: Exoskeletons for military personnel allow for enhanced endurance and reduced fatigue during prolonged missions, with one DOF configurations employed in the hip or knee joints.

The control of exoskeletons with one DOF kinematic linkages can be straightforward, focusing on transferring user intent to movements. Various control strategies include:

Sensor-Based Control: This approach uses sensors to detect user motion and intent, allowing the exoskeleton to respond in real time.

Myoelectric Control: Some systems use electromyography (EMG) signals from muscles to dictate the movement of the exoskeleton, enhancing the user's natural control over the device.

The starting point for the realization of a new rehabilitation exoskeleton robot solution is the robot leg mechanism shown in Fig. 1 [16]. It is based on a pantograph-type kinematic chain, which is driven by an articulated quadrilateral-type kinematic chain.

A patent was obtained for this innovative mechanism solution in 2021 [17]. As can be seen from the kinematic scheme shown in Fig. 1, the structural solution comprises 7 kinematic elements connected by 14 rotational couplings. So, the exoskeleton robot solution provides assistance only for the flexion/extension movements of the human leg, realized in the sagittal plane. In order to optimize this initial design, we proposed another kinematic scheme, shown in Fig. 2, which retains the pantograph-type kinematic chain in its structure, but the actuation is achieved by means of a Lambda-Chebishev-type kinematic chain. It can be seen that this solution also consists of 7 rod-type kinematic elements and 14 rotational kinematic torques.

The kinematic element (6) - through the FH segment structurally reproduces the femur bone of the human leg, and the kinematic element (7) - through the HM segment, reproduces the tibial bone of the human leg structure. In the structure of the mechanism, we also have the kinematic rotational couplings F and H, which structurally model the hip and knee joint of the human leg structure. Since this solution also assists human gait in the sagittal plane, the kinematic couplings in the leg structure will be considered rotational.

Therefore, we will analyze from a kinematic and dynamic point of view the behavior of the structural solution presented in Fig. 2. For this purpose, we will perform a synthesis of the dimensions of the kinematic elements, starting from the length of the human leg segments, for a human subject with the average dimensions of the sample considered when analyzing the biomechanics of human gait. Thus, in the first phase, we developed a 3D model of the mechanism proposed as a solution for the exoskeleton robot leg, as shown in Fig. 3.

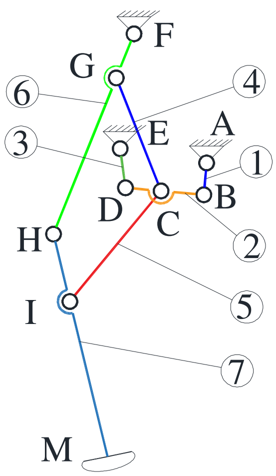


Fig. 1. Kinematic scheme of the initial solution.

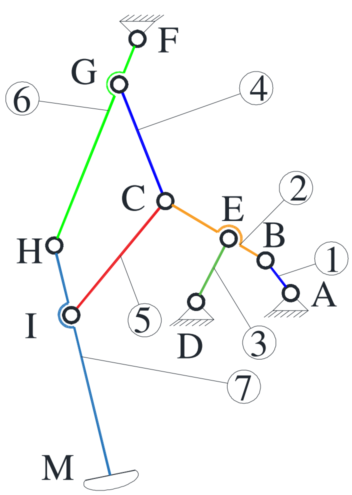


Fig. 2. Kinematic scheme of the newly proposed solution.

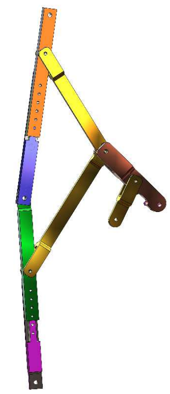


Fig. 3. The 3D model of the exoskeleton leg mechanism.

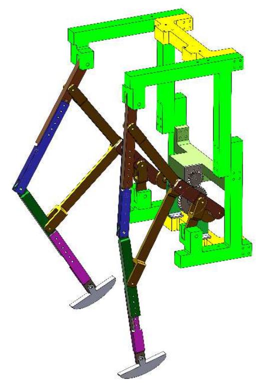


Fig. 4. Assembling the two mechanisms for the exoskeleton legs to the upper frame.

Obviously, it is necessary to build a frame to assemble the two mechanisms, which constitute the legs of the exoskeleton robot. Thus, in Fig. 4 shows the constructive details of this frame. It is designed to be realized by rapid prototyping and screw assembly. The stiffening element in the middle, also serves for the mounting of the drive motor, which by means of a gear transmission, Fig. 5, powers the driving elements.

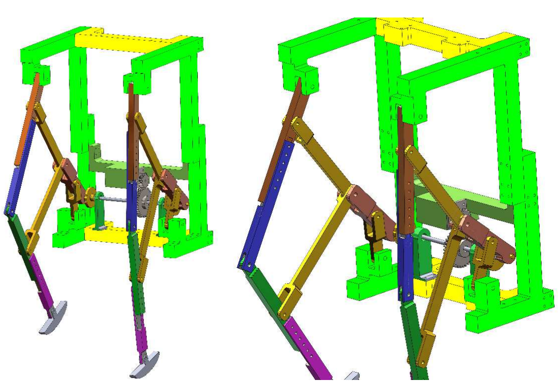


Fig. 5. Details of mounting the mechanism elements on the upper frame.

It can be seen that we have modeled the kinematic elements, with a fork-like design, for the mounting of axles, which will constitute the rotational joints. One aspect that we had in mind when realizing this constructive solution, is the maximum size to which we can realize the elements by rapid prototyping, which is 400 mm. Thus, we opted for the upper frame by joining two elements, connected with stiffening cross members.

The aim of the design is in the first phase to realize a kinematic simulation of the exoskeleton system in order to compare the movement of the leg mechanisms with the movement of human subjects. Thus, in the first phase we will perform the motion simulation of the robotic system when operating with the upper frame fixed to the base.

For the kinematic simulation, we used the software for dynamic analysis of multibody systems-ADAMS.View. We obtained by numerical simulation in ADAMS the trajectories realized by the M-point of the exoskeleton leg mechanism. The shape of the letter "D" type trajectory can be observed, in Fig. 6, where the linear portion corresponds to the propulsion phase of walking and the adjacent portion corresponds to the swing phase.

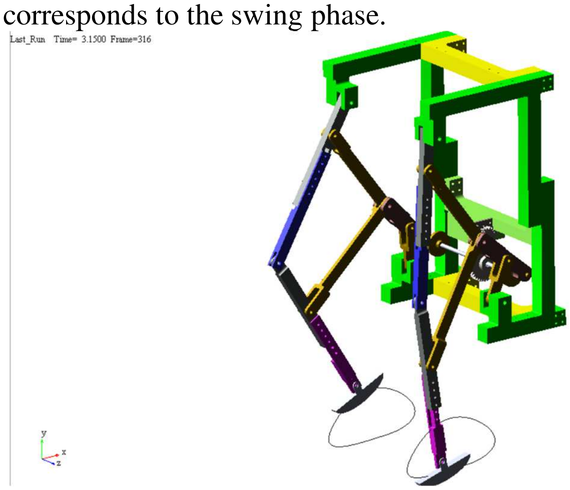


Fig. 6. The trajectory realized by point M, when operating the exoskeleton with the upper frame attached to the base.

In this operating situation of the exoskeleton, it is of interest to determine by ADAMS simulation the angles in the kinematic joints F and H, corresponding to the human hip and knee joints. Thus, Fig. 7 shows the variation law of the angle in the F-joint, which corresponds to the hip. It can be observed that the amplitude of the hip angle is 37 deg.

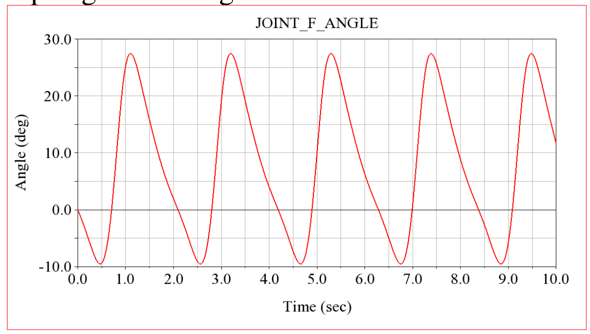


Fig. 7. Law of variation of the F-joint angle of the hip exoskeleton.

Another result of interest is rendered in Fig. 8, namely the law of variation of the rotation angle in the kinematic H-couple, which structurally models the human knee. According to the obtained variation, we notice the angular amplitude of 58 deg.

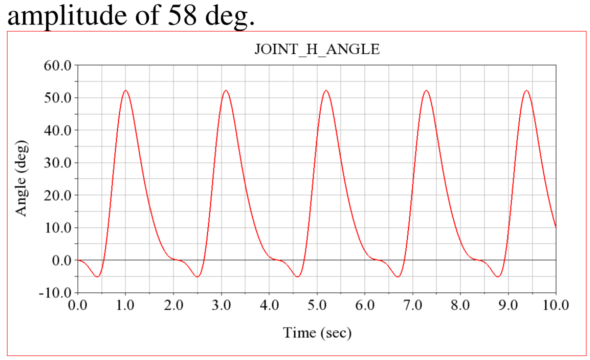


Fig. 8. Law of variation of the angle in the H-joint - which is related to the knee of the exoskeleton.

In Fig. 9, 10 and 11 the variation laws for the components of the positions, velocities and linear accelerations of the M-point of the sole of the foot mechanism are plotted. Note that their variation does not imply sudden jumps, i.e. the designed mechanism realizes movements that do not affect the assisted patient.

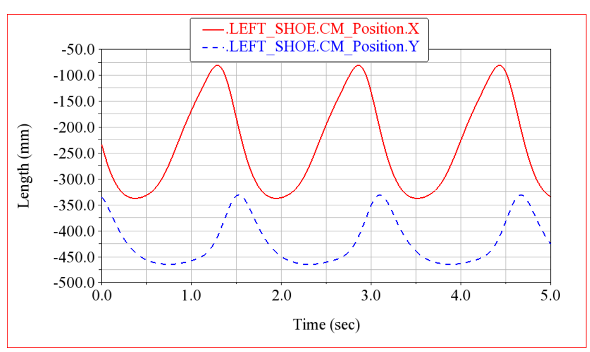


Fig. 9. The variation laws of the position coordinates of point M along the X-horizontal and Y-vertical axes.

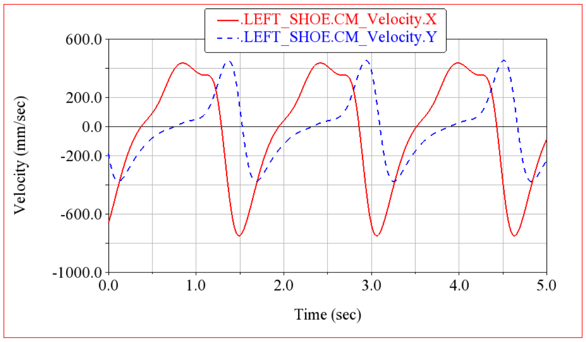


Fig. 10. The variation laws of the velocity components of the M point.

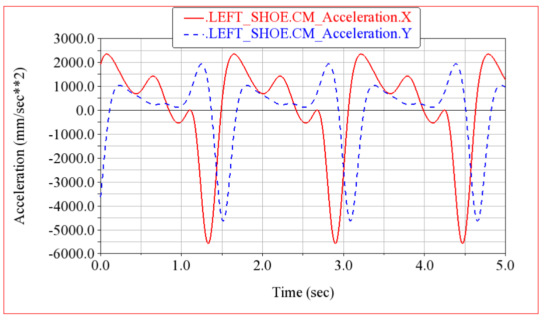


Fig. 11. The variation laws of the acceleration components of the M-point.

The second simulation hypothesis assumes the exoskeleton walking on a flat surface, as shown in Fig. 12. For this simulation hypothesis, the most important aspect is the definition of the contact between the exoskeleton sole and the ground. The setting of the contact parameters, namely stiffness, contact force exponent, and damping, is done according to existing data in the literature [10].

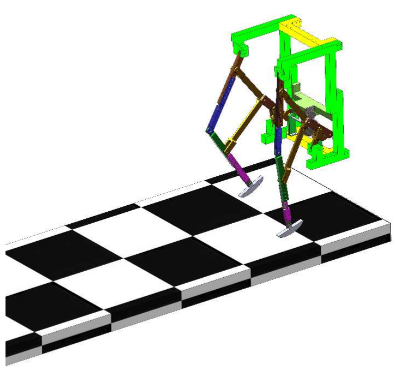


Fig. 12. Second simulation scenario, where we simulate the exoskeleton walking on the floor.

For this simulation hypothesis, the trajectory realized by the exoskeleton feet is shown in Figure 13.

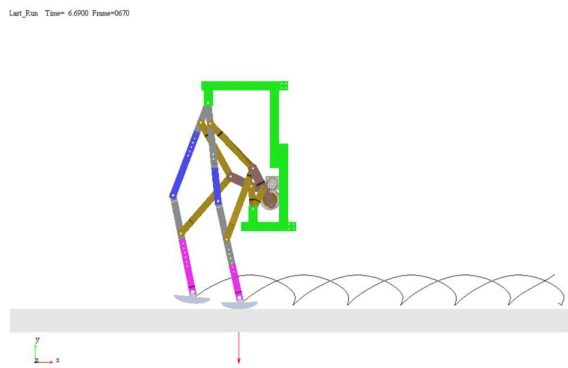


Fig. 13. The trajectory described by the M-point of the leg mechanisms, obtained when the exoskeleton walks on the floor.

A sequence of successive frames, where we initially have the left leg in contact with the ground, then the right leg of the exoskeleton will be in contact with the ground, is shown in Fig. 14.

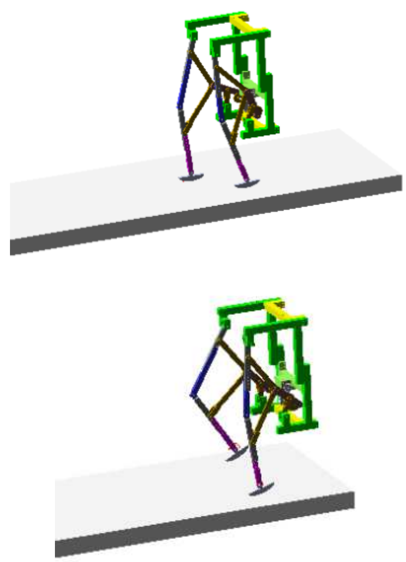


Fig. 14. Successive frames related to the movement of the exoskeleton on the ground.

In this simulation hypothesis, since we considered that the weight force of an average sized human subject, i.e. 700 N, acts on the upper frame, we obtained the variation laws for the kinematic joints connecting forces and their components. Thus, we will present in the paper only the results obtained for the connection forces in the couplings H and F. For the joint H, related to the knee of the leg of the exoskeleton, we have presented in Fig. 15, the variation law of the resulting reaction in the coupling, and in

Fig. 16 we have presented the variation laws of the components along the X and Y axes.

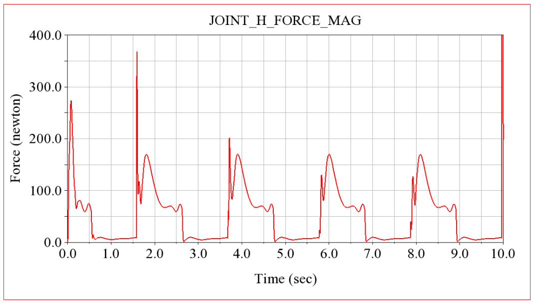


Fig. 15. The law of variation of the resultant reaction in the kinematic H-couple during the exoskeleton's ground walking.

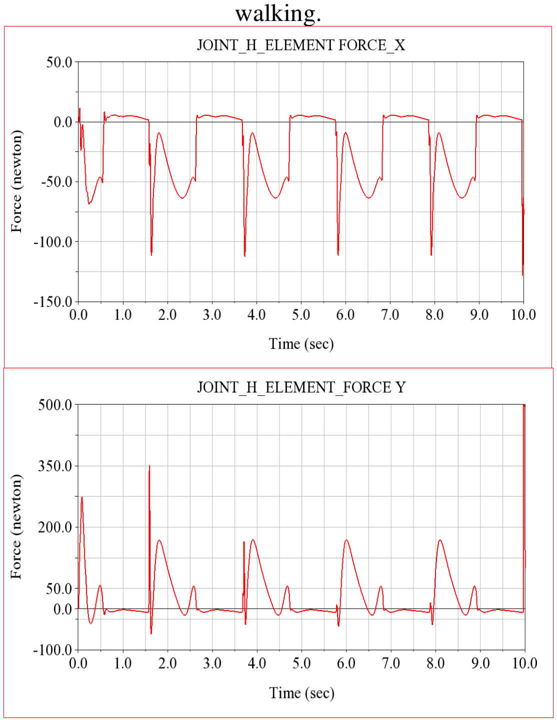


Fig. 16. Variation laws for the resulting reaction components in the kinematic H-couple during exoskeleton ground walking.

According to these obtained results, we note that the highest absolute value is recorded by the component along the vertical Y-axis, i.e. 160 N, without taking into account the peaks due to the contact shocks. For the hip joint, the law of variation obtained for the resultant connection force is shown in Fig. 17, and the laws of variation of the two components of the reaction in the F-couple are shown in Fig. 18.

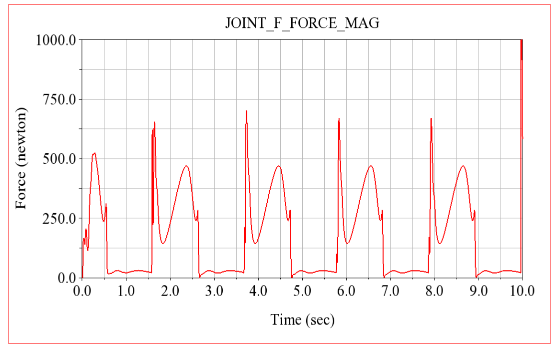


Fig. 17. The law of variation of the resultant reaction in the kinematic couple F, during the exoskeleton's ground walking.

Again, we note that the higher absolute value is recorded for the component along the Y-axis, 480 N, without considering the peaks from the contact force. At the same time, the resultant reaction recorded in the F-coupling is 480 N, and it is higher than the knee resultant reaction which is 170 N.

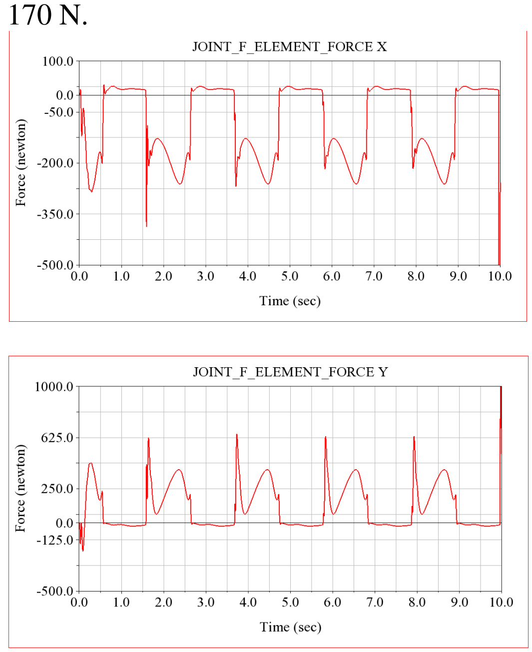


Fig. 18. Variation laws for the resultant reaction components of the kinematic coupling F during exoskeleton ground walking.

With reference to the motion of the exoskeleton on the floor, it is characterized by the laws of variation of the position of the point M, shown in Fig. 19 as the two coordinates X and Y, and in Fig. 20 as the resulting position.

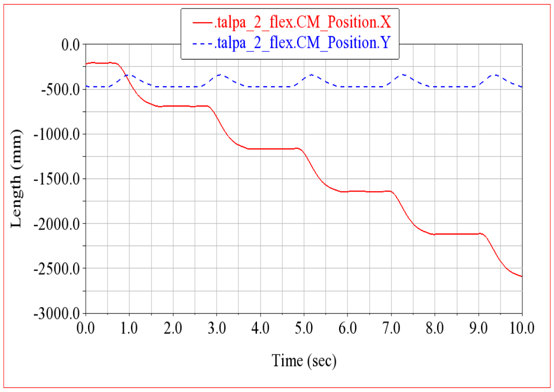


Fig. 19. The variation laws for the X and Y coordinates of the point M, during the exoskeleton's ground walking.

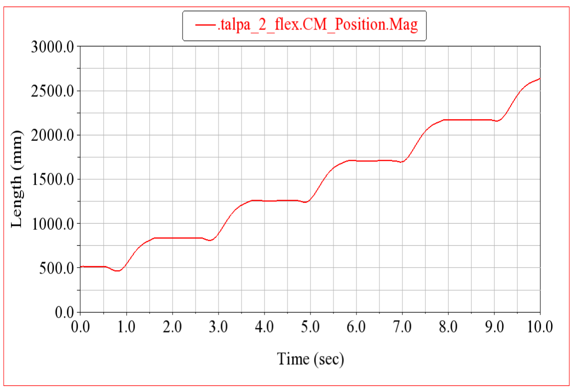
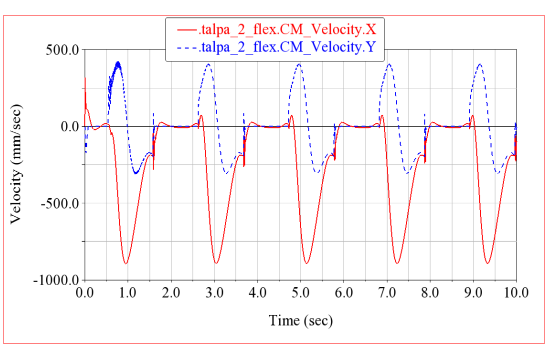


Fig. 20. Variation law for the resultant position coordinate of the point M, during the exoskeleton's ground walking.

Thus, according to the graph in Fig. 19, it can be seen that the displacement along the X-horizontal axis is realized in the opposite direction of this axis, over a distance of 2.5 m.

The number of steps realized by the exoskeleton, as shown in Fig. 20, i.e. 5 steps, is given by the number of portions with linear variation of the position of the point M.

Also, according to Fig. 21, the linear velocity of the point M does not show sudden variations while the exoskeleton is walking on the ground.



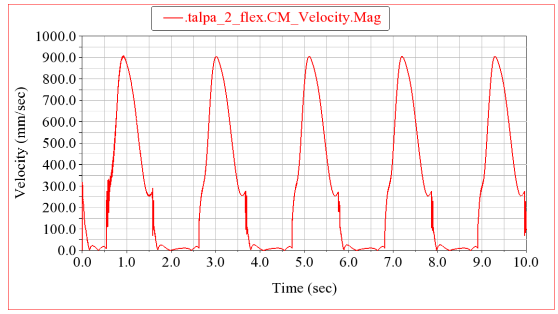


Fig. 21. The law of variation for the linear velocity of the M-point during the exoskeleton's ground motion.

4. CONCLUSION

Exoskeleton robotic systems, particularly those utilizing one degree of freedom (DOF) kinematic linkages in their leg designs, represent a significant advancement in assistive and rehabilitative technologies. These systems offer various advantages, including enhanced mobility, reduced fatigue, and improved rehabilitation outcomes for individuals with mobility impairments or those recovering from injuries.

The use of one DOF linkages simplifies the mechanical design and control, allowing for more straightforward actuation and motion planning. This can lead to lightweight structures that are easier to manufacture and maintain, thereby increasing accessibility for users. Additionally, these systems can be tailored to provide specific assistance, such as gait support during walking or stabilization during standing, making them versatile tools for rehabilitation.

While one DOF kinematic linkages offer several benefits, there are inherent limitations:

Range of Motion: The confinement to a single axis can restrict the range of movement and adaptability to complex tasks that require multi-directional mobility.

User Experience: Users may find it challenging to adapt to the limitation of movement, especially if the exoskeleton does not sufficiently mimic natural walking patterns.

Advancements in materials science, robotics, and artificial intelligence are paving the way for the next generation of exoskeletons:

Integration of Multi-DOF Systems: Future designs may incorporate multi-DOF systems to provide a more natural gait and versatile functionality.

Adaptive Control Algorithms: Machine learning could be leveraged to create adaptive systems that learn user preferences and enhance performance over time.

Wearable Technology: Combining exoskeletons with wearable technology for health monitoring could provide additional benefits, ensuring safe and efficient usage.

However, the limitations of one DOF systems are notable, particularly in their ability to replicate the complex and dynamic nature of human leg movement. While they can provide effective assistance in specific tasks, they may not fully accommodate the varied movements required for daily activities. Future developments may focus on integrating multi-DOF systems or advanced control algorithms that enhance adaptability and responsiveness to user intentions.

In conclusion, exoskeleton robotic systems with one DOF kinematic linkages hold great promise for improving mobility and rehabilitation. As technology progresses, ongoing research and innovation will be essential to overcome current limitations and create more complex exoskeletons that can better mimic natural human movements, ultimately leading to a higher quality of life for users.

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SINTEZA STRUCTURALĂ ȘI ANALIZA DINAMICĂ A UNUI NOU MECANISM DE ASISTENȚĂ LA MIȘCAREA PICIORULUI UMAN

Rezumat: *În această lucrare sunt prezentate aspecte privind structura, analiza cinematică şi dinamică a unui mecanism care este conceput pentru a fi implementat ca şi picior al unui robot de tipul exoschelet. Exoscheletul proiectat este destinat asistării şi reabilitării mersului uman, şi are particularitatea constructivă că mecanismul implementat în structura piciorului este mono-mobil. Asistența la mişcare este furnizată prin asistarea articulațiilor şoldului şi genunchiului. Astfel prin studiul cinematic sunt determinate legile de mişcare din articulațiile exoscheletului, care reproduc pe cele ale şoldului şi genunchiului uman, şi este realizată o comparație între legile de mişcare, şi anume amplitudinea unghiulară, realizată de exoschelet şi de un subiect uman sănătos.*
Cuvinte cheie: *exoschelet al membrelor inferioare, mers uman, proiectare mecanică, analiză dinamică, robot de reabilitare.*

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