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ASSISTIVE DEVICES FOR HUMAN LOCOMOTION ASSISTANCE AND REHABILITATION AT FACULTY OF MECHANICS – UNIVERSITY OF CRAIOVA

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Abstract: *This paper represents a review regarding the exoskeletons designed by researchers from the Faculty of Mechanics, University of Craiova, starting from conceptual design to prototypes and future works. Thus, the research aim is to identify the disadvantages, lack, and improvements of these assistive devices, from mechanical engineering and therapy procedures specific considerations. Several prototypes and concepts are presented, representing a fundamental base for future concepts and research directions.*

Key words: *Human walking, gait rehabilitation, design, prototypes, exoskeletons.*

1. INTRODUCTION

The first concepts of wearable exoskeletons emerged, driven by interests in augmenting human strength for industrial and military applications. General Electric's Hardiman, developed in the late 1960s, was among the earliest powered exoskeletons, though it was impractical due to its massive size and weight [1]. Research continued in academic and military contexts, with a focus on creating more practical and lighter systems. However, these early prototypes were still cumbersome and limited by the technology of the time.

The focus shifted towards rehabilitation and medical applications. Advances in robotics and materials science led to more feasible designs.

The University of Michigan developed the first computer-controlled lower limb exoskeleton aimed at assisting paraplegics in

The University of California, Berkeley, developed the Berkeley Lower Extremity Exoskeleton (BLEEX), which provided significant advancements in exoskeleton technology as in [2,3].

Japan's Tsukuba University introduced the HAL (Hybrid Assistive Limb) exoskeleton, one of the first exoskeletons designed specifically for assisting people with mobility impairments [4,5].

The exoskeleton market began to grow, with several companies developing and commercializing products for rehabilitation: originally spun off from Berkeley's robotics lab, Ekso Bionics released the EksoGT [6], a wearable bionic suit for rehabilitation purposes; founded in 2001, ReWalk [7] developed the ReWalk exoskeleton, which gained FDA approval in 2014 for use in clinical rehabilitation settings, a spin-off from UC Berkeley, introduced the Phoenix exoskeleton, designed for both personal and clinical use [8].

During the time mentioned the systems have benefit by: improved sensors, actuators, and AI integration. These have significantly enhanced exoskeleton capabilities, making them more responsive, adaptive, and user-friendly.

Nowadays current trends and future directions are oriented on personal use, AI and machine learning, regulatory approvals, and research development.

There is a growing trend towards making exoskeletons available for everyday personal use, not just in clinical settings.

Regarding the AI and Machine Learning, these technologies are increasingly being integrated into exoskeletons to provide more

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personalized and efficient rehabilitation programs.

More exoskeletons are gaining regulatory approval, expanding their accessibility and credibility in medical treatments.

Ongoing research focuses on making exoskeletons lighter, more affordable, and more effective in assisting with a wider range of mobility impairments.

Human walking rehabilitation exoskeletons have evolved from cumbersome, impractical machines to sophisticated devices that significantly improve mobility and independence for people with disabilities. The future holds promise for even greater advancements in this life-changing technology.

By having in sight the exoskeleton's summary evolution, there is a parallel between these systems and the ones developed during time at the Faculty of Mechanics, University of Craiova.

Thus, this research aims to summarize the performances and evolution of the designed exoskeletons especially designed for human locomotion systems rehabilitation inside of Faculty of Mechanics laboratories from University of Craiova.

The research is organized as it follows: first part represents a summary state-of-the art regarding the general evolution of the exoskeletons especially designed for human locomotion rehabilitation and walking assistance. Second part is dedicated for presenting some exoskeletons especially designed for walking and rehabilitation assistance in case of elderly persons and children. This represents the research core were it will be remarked the mechanical structure, advantages and disadvantages and performances given by the experimental results during prototype analyses.

Third part of the research will outlined the future works in case of the proposed subject and directions for increasing their performances.

At the end there will be presented conclusions of the analyzed systems.

2. EXOSKELETONS DESIGNED AT FACULTY OF MECHANICS

Among time, at Faculty of Mechanics laboratories from University of Craiova, there were designed several exoskeletons as a results of the research enterprise in PhD Thesis and research grants. Firstly there were analyzed prosthetic systems used in human mobility assurance during walking in [9].

After these several exoskeleton solutions were designed based on combining several mechanism types and actuation systems as it can be mentioned: test bed for children walking assistance and rehabilitation; exoskeleton for human walking assistance; exoskeleton for human neuromotor rehabilitation; exoskeleton for children walking assistance. But these are not all. Furthermore the mentioned systems will be presented from a structural viewpoint together with their peculiarities, advantages and disadvantages.

2.1 A test bed for children walking assistance and rehabilitation - LoCoPed

In 2010, after winning a National Grant Competition, a project began to rise which consists on designing a test bed for children walking assistance and recovery. This research grant was ended in 2012, and was finalized with a functional product, as it can be seen in Fig. 1.

Fig. 1. Test bed for children walking assistance [10]

The designed test-bed was characterized by a three main parts: a treadmill, an exoskeleton, and a special support for maintain the child weight.

The entire system was designed with adjustable mechanical devices in a manner that allow to be used by children with ages between 4 to 6 years.

The exoskeleton has all the main joints actuated through chain transmissions by six servomotors. The exoskeleton architecture is shown in Fig. 2. The command and control unit allow the user to adjust the angular variations developed by the exoskeleton during gait assistance.

The advantages of this rehabilitation system are: constructive simplicity and easy operation futures, adjustable links, reduced weight support for the child, adaptive treadmill speed during gait assistance.

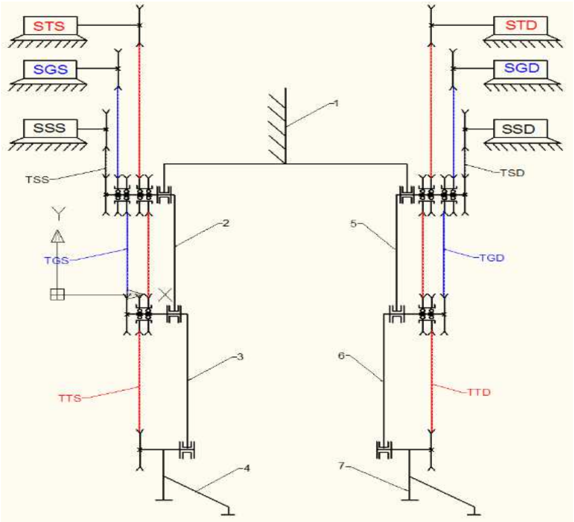

Fig. 2. A structural scheme of the exoskeleton [10]

Also, at that time period this has disadvantages like: poor contact between exoskeleton links and child legs, it can be used only in presence of a specialist and it cannot be used independently, the chain transmission gave an interrupted motion due to the polygonal effect of the chain wheels, the missing shells for protecting the child during motions for the chain transmissions, and so on.

2.2 Exoskeleton for human walking assistance - LoCoEx

Another exoskeleton used for walking assistance was developed in 2012 based on a mechanism combination namely Chebysev, pantograph and a cam mechanism for each leg [10] as it can be remarked in Fig. 3 and Fig. 4.

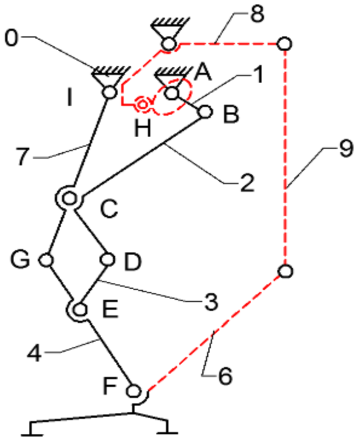

Fig. 3. A structural scheme of the leg exoskeleton

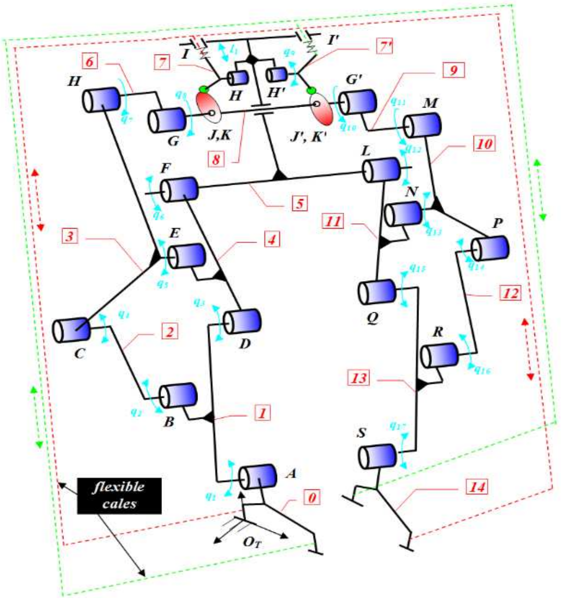

Fig. 4. A structural scheme of the exoskeleton [10]

The design principle was given by low-cost, easy-operation features, and simplicity. It is supposed to be actuated by a single servomotor, a central one as it can be seen in Fig. 4. First prototype was elaborated without cam mechanism for ankle joint actuation as it can be remarked in Fig. 5.

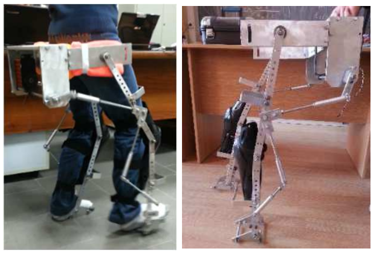

Fig. 5. Exoskeleton prototype without cam mechanism

Thus, this exoskeleton prototype has the main advantage of using a single servomotor unit for actuating six main joints of the human locomotion system only for walking. Another advantage is given by its mechanism configuration which can offer good results on the angular variations of the actuated joints, namely hips, knees, and ankles.

The disadvantages of this, are given by the contact limitations between exoskeleton links and human lower limbs, instability, its inability to be self-sustainable and to support the patient's weight, and foot contact which affects the exoskeleton workspace orientation during walking, the introduced cam mechanism at overloads, leads to malfunction of this.

2.3 Exoskeleton for human neuromotor rehabilitation - NeuRob

In 2018 it was elaborated an exoskeleton test rig for human neuromotor rehabilitation. This was financed through a National Grant Competition namely PNIII-P2-2.1-PED-2016-0934, under the lead of Prof. Dumitru Nicolae PhD. Eng.

This is a complex one, as it can be observed in the structural scheme presented in Fig. 6.

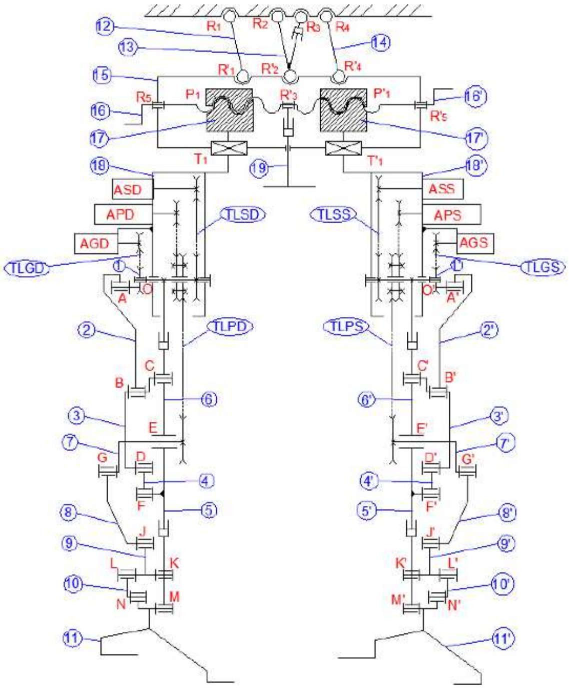

Fig. 6. Exoskeleton structural scheme [11]

From Fig. 6 it can be observed that each main joint is actuated through a chain transmission by a servomotor unit. Another particular aspect is the one given by the adjustable links sizes which allow the user to adjust the exoskeleton limb size. This exoskeleton was designed in order to contribute at the neuromotor deficiencies of persons with ages between 30 to 70 years old, weight between 50 to 90 kilograms and height between 1.50 to 1.90 meters.

Some snapshots and proper images of these are shown in Fig. 7.

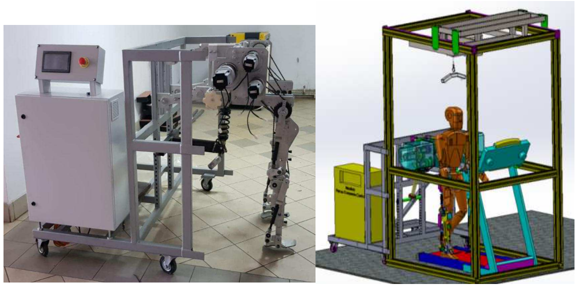

Fig. 7. NeuRob exoskeleton test rig [11, 12]

This rehabilitation system has the main advantages of adjustable link sizes and a fully actuated system for all six main joints that corresponds to the human locomotion system.

The disadvantage is given by the fact that it is a stand-alone system, it cannot be moved due to its weight, another problem is the chain transmissions used in its own actuation system, and this introduces additional reaction forces in the exoskeleton mechanism due to polygonal effect characteristic to a chain transmission. Also, this requires additional assistance assured through a specialist for using the NeuRob system.

2.4 Exoskeleton for children walking assistance - ExoDis

By having in sight the latest technology in Additive Engineering, namely 3D printing technology, this was a good opportunity to improve the advantages in case of exoskeleton designs and proper destinations. Thus, the latest version of an exoskeleton prototype was elaborated based on 3D printing technology, was designed based on previously mentioned versions and it was fully dedicated to children's walking assistance. Thus, this was characterized by the actuation of six main joints through a mechanism combination namely Chebysev, pantograph, and Stephenson III six-bar mechanism. A structural scheme is presented in Fig. 8 from [13].

The 3D printing technology offers a huge advantage by increasing the contact between the leg exoskeleton and the child's leg. This will give stability and improve the command and control functions. The elaborated prototype is shown in Fig. 9.

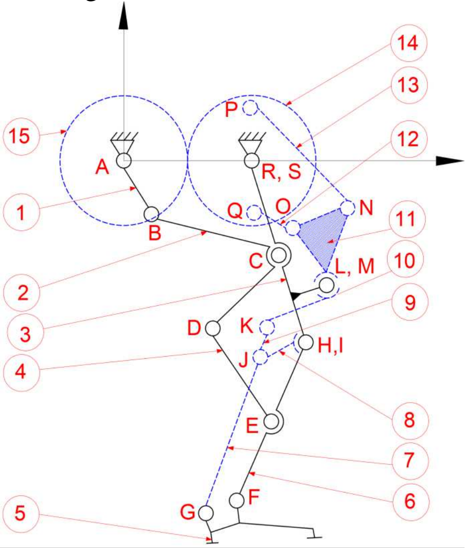

Fig. 8. Exoskeleton prototype structural scheme based on Chebysev, pantograph and Stephenson III six-bar mechanism [13]

Fig. 9. Exoskeleton prototype with Chebysev, pantograph and Stephenson III six-bar mechanism for children walking assistance

Other advantages are given by: lightweight; autonomy, the control unit is radio-controlled and can be used on a radius of 30 meters; it is self-stable due to its designed frame which assures steering and protection for the child and exoskeleton falling down; ground contact improvement by printing the foot components from a material with a rough surface for a good contact and an increased adherence during walking; a controlled workspace orientation by the user, due to the frame which has a steering system designed for front wheels. Also, this has disadvantages like the volume of this is big, and it can be minimized; it doesn`t have the components with adjustable sizes; implementing the Stephenson III six-bar mechanism, increases the exoskeleton complexity.

3. RESULTS AND DISCUSSIONS

By having in sight the presented rehabilitation systems especially designed for walking in case of adults and children, the prototypes validation was done through experimental analyses and comparative analyses with the ones existent in special literature like [14]. Thus it can be remaked two exoskeleton groups, namely one designed for children – ExoDis and LoCoPed, other designed for adults – NeuRob and LoCoEx.

Among time, the results of the experimental analyses were published by the authors in extended versions. Thus, for evaluating the experimental analyses numerical results in terms of performance, it can be summarized for one leg namely the left lower limb from each exoskeleton, and these are represented in diagrams.

For the first group was obtained the diagrams reported in Fig. 10 to Fig. 12, where it can be observed the angular variations for the main analyzed joints. The results were numerically processed with the aid of LS-Dyna, based on experimental analyses carried out with high-speed motion capture equipment. This corresponds for a complete gait in terms of 100%. The graph reported in Fig. 10 it can be remarked that in case of both analyzed prototypes the hip angular variation is almost appropriate to a natural joint developed in case of a child. Also, the angular variations are between 13.5 degrees and -23 degrees which results a total angular amplitude of 36.5 degrees.

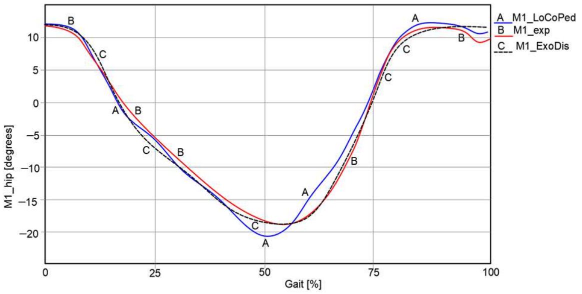

Fig. 10. Hip angular variation in case of a healthy child vs. ExoDis and LoCoPed for a complete gait

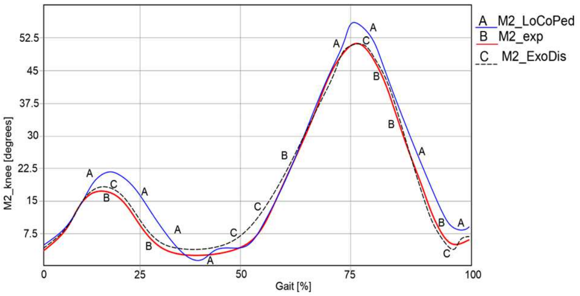

Fig. 11. Knee angular variation in case of a healthy child vs. ExoDis and LoCoPed for a complete gait

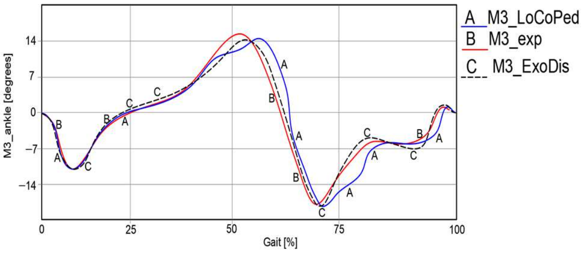

Fig. 12. Ankle angular variation in case of a healthy child vs. ExoDis and LoCoPed for a complete gait

A major remark is given by the path of the LoCoPed exoskeleton which is out of pattern when the gait records value between 45% to 57%. This will affect the other analyzed joints behavior. By considering the plot from Fig. 11, it can be remarked that the analyzed knee joint records angular variations between 5 degrees to 55 degrees, which means an angular amplitude of 60 degrees. This high values were recorded in case of the LoCoPed exoskeleton, and in this case it can be remarked some pitches around 35% and around 92% of a complete gait. In case of ExoDis, this has a fine copy of the children path.

In graph from Fig. 12, there are analyzed the results of ankle joint in case of three cases. For these there were recorded angular variations between 15 degrees and -17 degrees, which result an angular amplitude of 32 degrees. Again, this was recorded in the case of LoCoPed. The ExoDis exoskeleton represents a fine copy of the healthy child and in case of LoCoPed it can be remarked different paths between 60% and 90% of a complete gait. The results reported in Fig. 10, Fig. 11, and Fig. 12, corresponds with the literature reference data as in [14].

In case of the second group, there were evaluated the NeuRob and LoCoEx, in a similar procedure like previous group. Thus, the obtained results are shown in Fig. 13 to Fig. 15.

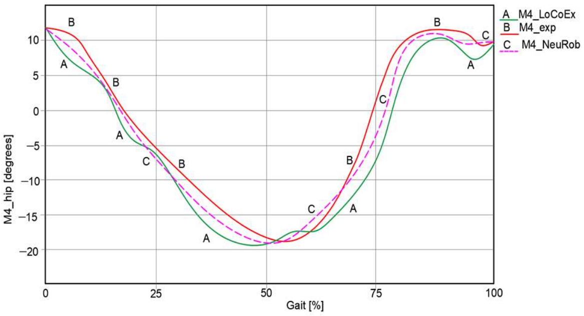

Fig. 13. Hip angular variation in case of a healthy adult vs. NeuRob and LoCoEx for a complete gait

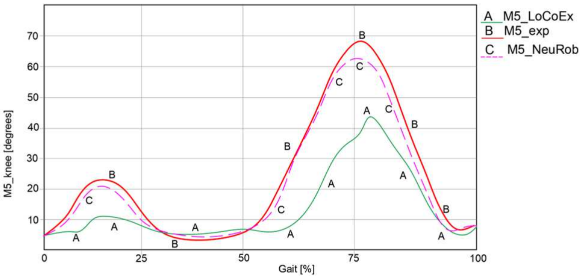

Fig. 14. Knee angular variation in case of a healthy adult vs. NeuRob and LoCoEx for a complete gait

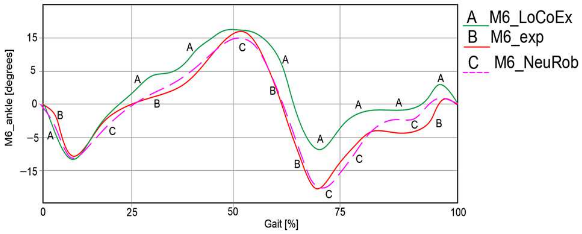

Fig. 15. Ankle angular variation in case of a healthy adult vs. NeuRob and LoCoEx for a complete gait

By having in sight the plots reported in Fig 13, Fig. 14, and Fig. 15, it can be remarked that the suitable exoskeleton who can copy the path of a healthy subject is NeuRob. The other one namely LoCoEx has lack of working due to the imprecise command and control offered by the cam mechanism. In case of the hip joint, the angular variation was between 10 degrees to almost -20 degrees, which respects the reference limit from [14]. Thus, it had resulted in an angular amplitude of 30 degrees, as it can be observed in Fig. 13. In case of knee joint, the angular variations was between 5 to 68 degrees, and in this case the angular amplitude was 73 degrees, as it can be remarked from Fig. 15. This is a little bit higher than the ones reported in [14].

At last, the ankle joint motions reported in Fig. 15 have a variation between -18 degrees to 16 degrees. For this, the angular amplitude will reach a value of 34 degrees in case a complete gait. For the second group the superior and appropriate values and paths corresponds to NeuRob, the other one it seems the cam mechanism is not the suitable mechanism for obtaining a good behavior of the entire exoskeleton and also this affects the other analyzed joints.

4. FUTURE WORKS

By having in sight the latest developed exoskeleton prototype, it can be remarked that the 3D printing technology represents a good direction to use in manufacturing the prototype. Moreover, it will be outlined the idea to use this for printing exoskeletons at a proper scale suitable for children walking assistance which is a prior in future research. Thus, in background an idea was rised to simplify the latest exoskeleton from a mechanical viewpoint, to insert a proper mechatronic actuation system and to combine this with croches or with children commercial frames like Kaye Walker [15] as it can be sketched in Fig. 16.

5. CONCLUSIONS

In this research, there are presented several exoskeleton developed among time in Faculty of Mechanics laboratories from University of Craiova. These are presented in order to illustrate the evolution and improvements of these in this multidisciplinary research area.

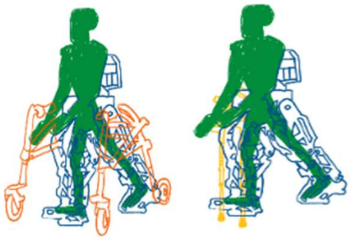

Fig. 16. Future prototype Exoskeleton Prototype

There are outlined the peculiarities, advantages and disadvantages in accordance with the obtained results shown by graphs of angular variations.

This research was done in order to identify future directions and also viewpoints that can mark the idea of commercializing these in accordance with the Technology Readiness Level TRL. Thus, in the mentioned prototypes the TRL's highest value was obtained in the case of the exoskeleton dedicated to neuromotor rehabilitation and the one for children's walking assistance. The TRL level for these ones reaches the value of 5 to 6.

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Dispozitive asistive pentru asistența si reabilitarea locomoției umane la Facultatea de Mecanica – Universitatea din Craiova

Rezumat: Aceasta lucrare reprezintă un raport asupra sistemelor de tip exoschelet proiectate de catre cercetători ai Facultatii de Mecanica – Universitatea din Craiova, pornind de la proiectarea conceptuală a acestora până la prototipuri. Astfel, scopul acestui articol este de a identifica dezavantajele, problemele și elementele de îmbunătațire ale acestor dispozitive asistive, plecând de la considerații specifice ale ingineriei mecanice și ale procedurilor terapeutice. Sunt prezentate câteva prototipuri și concepte, iar această cercetare reprezintă o bază fundamentală pentru concepte și direcții de cercetare viitoare.

Cuvinte cheie: *Mersul uman, reabilitarea mersului, design, prototipuri, exoschelete.*

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