TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 64, Issue Special II, February, 2021

MODELING AND EVALUATION OF A NEW EXOSKELETON USED FOR REHABILITATION OF OSTEOARTHRITIC HUMAN KNEE

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Abstract: *The first objective of this paper is to develop the virtual model and physical prototype of a new exoskeleton, useful for the stabilization and rehabilitation of the human osteoarthritic knee (OA). The second objective is to validate the proposed exoskeleton using numerical and experimental results of the average exoskeleton cycle. An experimental study is provided to compare the amplitude and shape of mean cycles of knee flexion-extension angles of the exoskeleton, of a sample of eight healthy subjects, a sample of six patients with OA knees, before and three months after total knee replacement.*

Key words: *Exoskeleton, osteoarthritic knee, prosthetic knee, kinematic analysis, experimental test*

1. INTRODUCTION

Nowadays, the biomechanical evaluation of human gait has an increased interest and it is often used for the development of rehabilitation systems such as orthotic devices [1-4], exoskeletons and medical robots used in rehabilitation [5-13].

The rehabilitation systems have a major contribution to the successful development and completion of rehabilitation programs. Wearable systems play a very important role in the case of rehabilitation procedures inside patients' homes.

The assistive exoskeletons represent an important segment on the current medical market [13-15], and many developed countries have begun to develop different types of exoskeletons were designed for assistive purposes, such as lower limb robotic exoskeletons for walking assistance [16, 17].

Recent research in the field of assistive devices such as orthoses, prostheses and exoskeletons are performed in order to help people with amputee limbs [18] or muscle dysfunction for lower limbs [18] as well as for upper limbs [19-23].

Assistive exoskeletons aim to rehabilitate the neuromusculoskeletal function of patients after surgery or those who have suffered a stroke, but can also be used to help the elderly or patients with mobility disorders during demanding daily activities [24, 25].

The researchers developed different solutions of knee exoskeletons, function of actuators and mechanisms. In [26] the authors proposed a KE actuated by pneumatic artificial muscles; in [27] a device based on rotary series elastic actuator is proposed, while in [28] two DC motors in combination with five bar linkage was presented. In study [29] a solution based on four-bar mechanism using EMG and force sensor for gait rehabilitation is shown, while in [30] a robot based on four-bar mechanism for the knee joint rehabilitation is proposed. In [31] the researchers investigated a KE actuated by linear SEA. In paper [32] a device for prevention of falling during walking based on compliant elements is proposed. A solution for increasing of the balance and strengthening the weak muscles was proposed in [33], while in [34, 35] the actuation system for parallel robots are presented.

In the present paper we present the design and the physical prototype of a new exoskeleton proposed to be used for the rehabilitation of the osteoarthritic human knee. In order to validate the design, experimental walking tests are provided and the medium walking cycles computed from the mathematical model are compared with the ones obtained by performing experimental evaluation of the exoskeleton and of the healthy and osteoarthritic knees.

2. EXPERIMENTAL STUDY

The aim of the experimental study is to evaluate and to obtain biomechanical data of the human joints angle variation. The information helps us to compare the exoskeleton and human movement with the purpose to improve the exoskeleton movement. The experimental study was performed using the data acquisition system Biometrics Ltd. The system is based on wearable sensors dedicated to biomechanical evaluations, which allow obtaining and analyzing the kinematic parameters for the human joints [36-39]. The technology of the system is based on wearable sensors, such as electrogoniometers allowing data collection with high accuracy and high real-time acquisition rate, but also ambulatory monitoring of medical research data, monitoring of human performance in activities carried out outside the laboratory, including normal walking activities, fast walking, running, jumping, etc. The integrated 3D motion analysis system can be coupled with force platforms, accelerometers, EMG sensors, without the need for prior synchronization, or calibration.

The main electrogoniometers features (figure 1a) are:

• Minimum operating time: 600,000 cycles;
• Accuracy: ± 2º 90º; measured range;
• Repeatability: 1º 90º measurement interval

The DataLOG data acquisition unit (Figure 2b) is a device that allows the collection of both analog and digital data, from a maximum of 24 sensors simultaneously, with frequencies up to 20,000 Hz. The main features of this mobile data acquisition device are: automatic digital filter (approximately 3dB at 0.45 x sampling rate) and a maximum attenuation of 13dB over 0.8 x sampling rate [38].

Data transfer is done in real time to a PC using Bluetooth®, providing real-time data transfer and display, but in the absence of a computer, data can be stored on a memory card attached to the device.

a) b)

Fig. 1. a) Electrogoniometers b) DataLog

In the present study were used two 8-channels DataLOG devices, at a frequency of 500 Hz, and six electrogoniometers mounted on the main six joints of the lower limbs. The block schema of the data acquisition process is shown in figure 2.

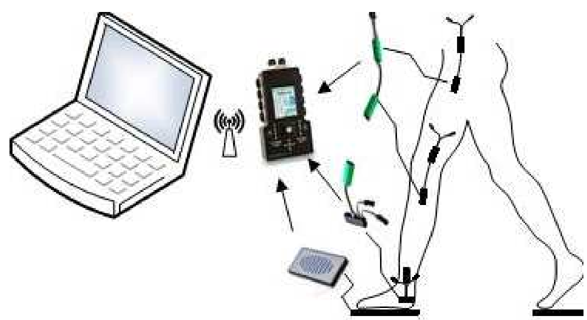


Fig. 2. Schema - block of the data acquisition process

The experimental study involved a sample of 9 healthy subjects and a sample of 6 patients suffering of osteoarthritic knee. The medium values and standard deviations of the main anthropometric data are presented in Table 1 for healthy subjects and in Table 2 for patients:

Table 1

Healthy subjects - anthropometric data

	Age [years]	Weight [kg]	Height [cm]	Leg length [cm]
Mean	26,8	67.3	174.4	79.8
StdDev	1.5	12.5	8.3	9.5

Table 2

Patients - anthropometric data

	Age [years]	Weight [kg]	Height [cm]	Leg length [cm]
Mean	60.2	74.1	169.3	81.6
StdDev	2.7	2.9	2.1	3.2

Each subject and patient performed five trials of 20 consecutive normal walking cycles on the ground surface. Each subject and patient was equipped with electrogoniometers and DataLog devices as is presented in figure 3.

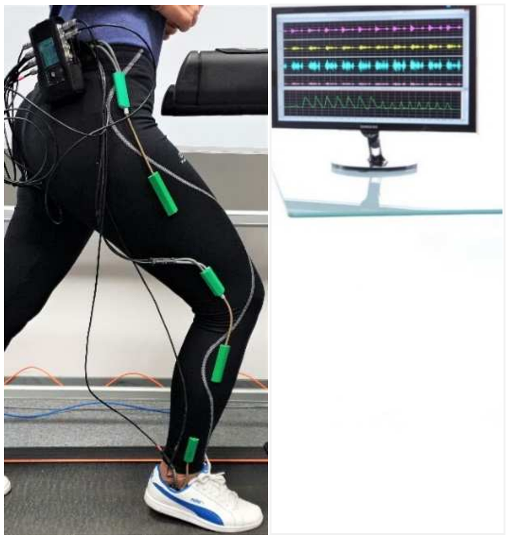


Fig. 3. Subjects with electrogoniometers

The data collection process is realized in real-time. The electrogoniometers, which are mounted on each joint, collected the kinematic data and send them to DataLog. The device synchronized the collected data and transferred to PC via Bluetooth where are converted in diagrams as are presented in figure 4.

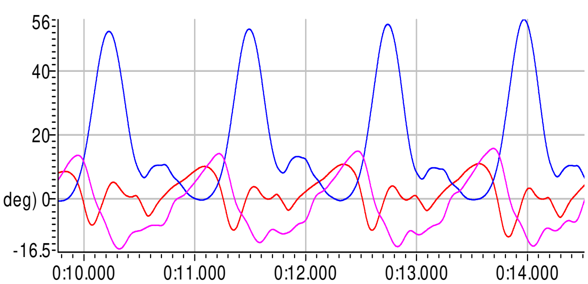


Fig. 4. Diagrams of consecutive cycles of variation of flexion-extension

To ensure the accuracy of the results, for each data file the data processing starts with the division of consecutive cycles into phases, after, previously, 3 cycles from the beginning and 3 cycles from the end of the data series have been eliminated. The remaining data represent a number of 14 cycles corresponding to a stable walking. In figure 5 the defining of the interval used for the division of walking cycles into phases is presented.

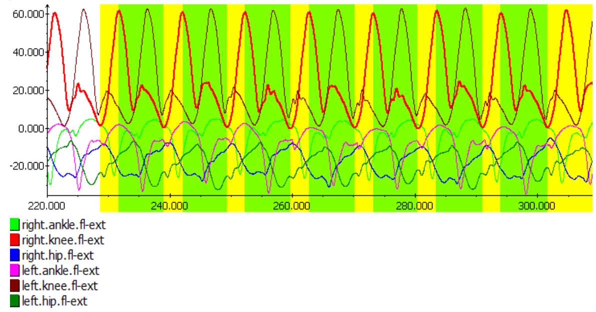


Fig. 5. Defining the interval used for the division into phases

Walking variability is a characteristic of human biomechanical behavior and is found in the comparison of each human individual to another, but also in the comparison between the walking cycles of the same individual. That is why it is necessary to first normalize the consecutive cycles on an abscissa of 100%, and to obtain the average cycle for each subject, and then, at the sample level. Using the SimiMotion software [40], each kinematic data series was processed to obtain the medium normalized gait cycle. In figure 6 the 14 consecutive cycles and the medium cycle (red color) computed for healthy Subject 1 are presented.

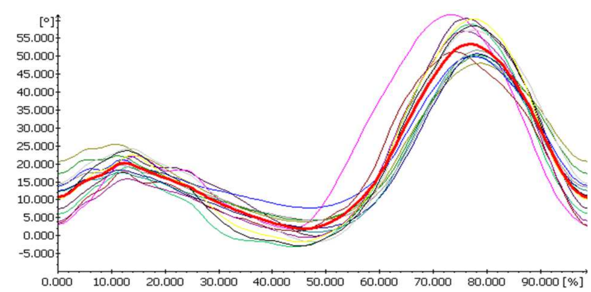


Fig.6. Diagrams of the 14 consecutive normalized cycles and the medium normalized cycle for Subject 1

In a similar manner, the medium cycle at the level of healthy subjects' sample and of patients' sample are obtained. In figure 7 the diagram of the mean cycle of knee flexion-extension angle for the knee of healthy sample is shown, while in figure 8 and 9, the similar medium cycle for the osteoarthritic knee of patients' sample before total knee arthroplasty and two months after total knee arthroplasty are shown.

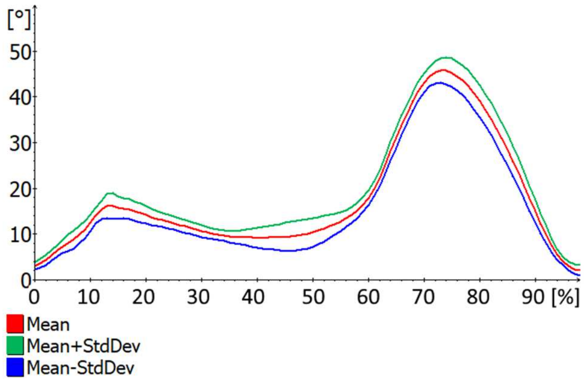


Fig. 7 Mean cycle of knee flexion-extension angle for healthy subjects

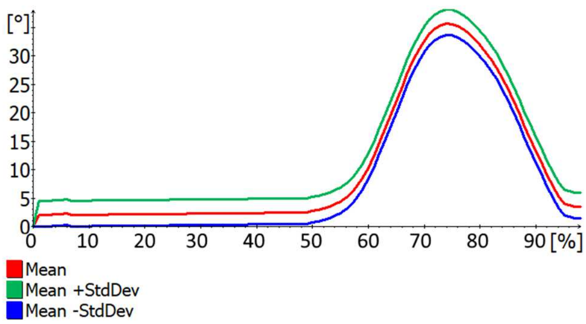


Fig. 8. Diagram of the mean cycle of osteoarthritic knee, before total knee arthroplasty

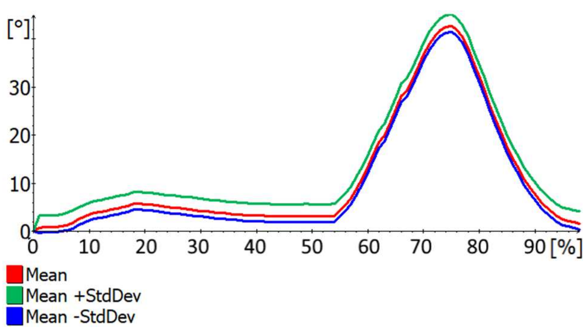
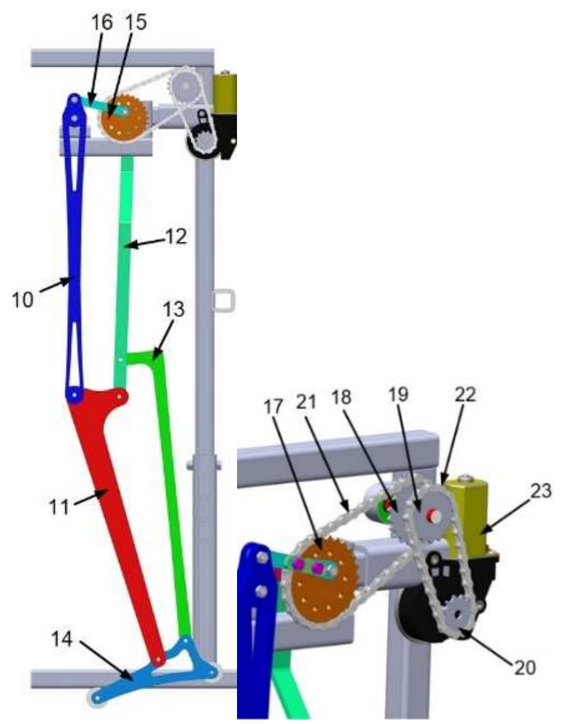


Fig. 9. Diagram of the mean cycle of osteoarthritic knee, after total knee arthroplasty

From the figures 7-9 the difference between the amplitude of the medium cycle of the knee flexion-extension angle of healthy subjects (48°) and that of the osteoarthritic knee before (36°) and after the operation (41°) can be observed. The shape of diagrams also differs from one to other.

3. EXOSKELETON DESIGN

In figure 10, the virtual model of the exoskeleton proposed for the rehabilitation of lower limbs and detailed information of the transmission system are shown The model is presented in detail in [7]. In figure 10, the components of the virtual model are noted as follows: element 10 - corresponding to the femur; element 11 - corresponding to the tibia; element 12 – necessary to achieve the flexion-extension of the knee; element 13 – necessary to achieve the flexion-extension of the ankle; element 14 – corresponding to the foot; elements 15 and 16 – are necessary for adjusting the amplitude of the flexion-extension; chain sprocket 17 - converts the rotation of the electric motor into a pivotal movement of the elements 13 and 10; gears 18, 19 and 20 are part of the power transmission system, while 21 and 22 are the power transmission chains; element 23 - electric motor.



a) b)

Fig. 10. a) The virtual model of the lower limb of the exoskeleton, b) detail of power transmission system

One of the main features of exoskeleton is that can be adjusted to recover the joints movement for both lower limbs and just for a single lower limb. Another feature of this device is the modularity; the exoskeleton dimensions can be adapted depending on the anthropometric patients' dimensions.

4. KINEMATIC ANALYSIS

To validate the mechanism functionality, we propose to achieve a kinematic analysis calculated using Maple software. In figure 11 the kinematic scheme of the mechanism is presented. The mechanism presents in its structure three dyads of RRR types: BCD, EHF, JGK. The lengths of the elements are known: l_{AB}=11mm, l_{BC}=91mm, l_{CD}=36mm, l_{CE}=480mm, l_{AF}=20mm, l_{FH}=461mm, l_{GH}=61mm, l_{GK}= 465mm, l_{EJ}=451mm.

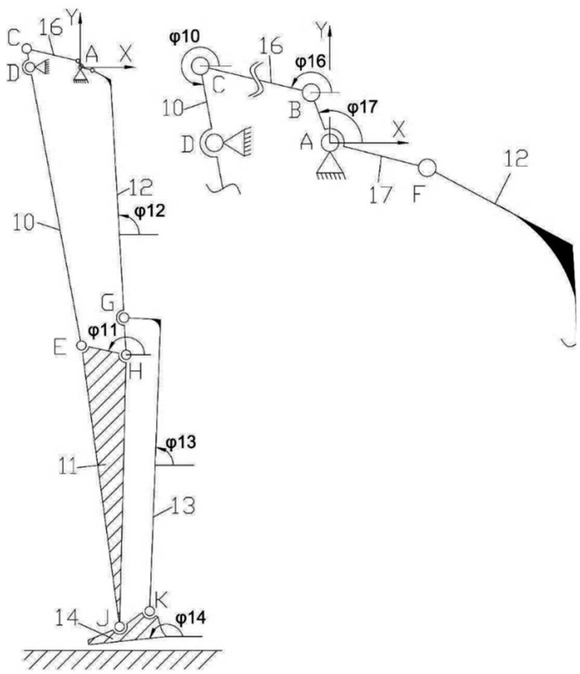


Fig. 11. The kinematic scheme of the exoskeleton leg

The equations of positions for the driving element:

$$\begin{cases} X_B = X_A + l_{AB} \cdot \cos\phi_{17} \\ Y_B = Y_A + l_{AB} \cdot \sin\phi_{17} \end{cases} \quad (1)$$

The equations of positions for dyad BCD:

$$\begin{cases} X_C = X_B + l_{BC} \cdot \cos\phi_{16} = X_D + l_{CD} \cdot \cos\phi_{10} \\ Y_C = Y_B + l_{BC} \cdot \sin\phi_{16} = Y_D + l_{CD} \cdot \sin\phi_{10} \end{cases} \quad (2)$$

The equations of positions for E joint**:**

$$\begin{cases} X_B = X_D + l_{DE} \cdot \cos(\phi_{10} + \pi) \\ Y_B = Y_D + l_{DE} \cdot \sin(\phi_{10} + \pi) \end{cases} \quad (3)$$

The equations of positions for F joint**:**

$$\begin{cases} X_F = X_A + l_{AF} \cdot \cos(\phi_{17} + 235^{\circ}) \\ Y_F = Y_A + l_{AF} \cdot \sin(\phi_{17} + 235^{\circ}) \end{cases} \quad (4)$$

The equations of positions for FHE dyad:

$$\begin{cases} X_H = X_F + l_{FF'} \cdot \cos(\phi_{12} + \pi - \beta) + l_{F'H} \cdot \cos\phi_{12} \\ = X_E + l_{EH} \cdot \cos\phi_{11} \\ Y_H = Y_F + l_{FF'} \cdot \sin(\phi_{12} + \pi - \beta) + l_{F'H} \cdot \sin\phi_{12} \\ = Y_E + l_{EH} \cdot \sin\phi_{11} \end{cases} \quad (5)$$

where β=121°

The equations of positions for G joint:

$$\begin{cases} X_G = X_F + l_{FF'} \cdot \cos(\phi_{12} + \pi - \beta) + l_{F'G} \cdot \cos\phi_{12} \\ Y_G = Y_F + l_{FF'} \cdot \sin(\phi_{12} + \pi - \beta) + l_{F'G} \cdot \sin\phi_{12} \end{cases} \quad (6)$$

The equations of positions for J joint:

$$\begin{cases} X_J = X_E + l_{EJ} \cdot \cos(3\pi - \phi_{11} + \alpha) \\ Y_J = Y_E + l_{EJ} \cdot \sin(3\pi - \phi_{11} + \alpha) \end{cases} \quad (7)$$

where α=70°

The equations of positions for dyad JKG:

$$\begin{cases} X_K = X_G + l_{GG'} \cdot \cos(\phi_{13} - \pi/2) + l_{G'K} \cdot \cos\phi_{13} \\ = X_J + l_{JK} \cdot \cos\phi_{14} \\ Y_K = Y_G + l_{GG'} \cdot \sin(\phi_{13} - \pi/2) + l_{G'K} \cdot \sin\phi_{13} \\ = Y_J + l_{JK} \cdot \sin\phi_{14} \end{cases} \quad (8)$$

The velocity equations are obtained by deriving the position equations (1-8) with respect to time, while the acceleration equations are obtained by deriving the velocity equations with respect to time.
The positions, the velocities and the accelerations were calculated using Maple software [41].

5. BIOMECHANICAL EVALUATIONS OF THE PHYSICAL PROTOTYPE OF THE EXOSKELETON

The proposed solution is a low-energy solution for driving the entire device, using a single rotating motor, which is driven by a chain drive. The device has 8 elements and 10 rotating spindles in structure. The design of the metal frame has multiple functions: simple structure, modularization, more ergonomic and safer.

In terms of mechanical model and drive system, as well as size, shape and overall appearance, the design of the exoskeleton is similar to the human lower limb. The size and mass characteristics of the lower limbs have been studied to use them as input data in the exoskeleton design.

The prototype was completed in several stages. First, the metal frame was manufactured, then the lower limbs and gear components were manufactured, and finally they were assembled on the metal frame. In figure 12, the physical prototype of the exoskeleton and the sequence obtained from the steps performed by the exoskeleton are given. In the case of the lower limbs, the material used is metal plate with a thickness of 3 mm. The solution chosen for the manufacture of sheet metal parts is laser cutting because the cutting accuracy is much higher than that of traditional mechanical cutting, and because the deformation of the material in the cutting area is much lower than that of traditional mechanical processing [42]. The sprocket is also processed by laser cutting, the only difference is that the thickness of the plate used is 1.5 mm.

Fig. 12. The physical prototype of the exoskeleton- three sequences of a walking cycle

The purpose of this evaluation is to determine information of the exoskeleton joints angle variation. For this purpose, the Biometrics devices were used, on each joint of the exoskeleton, was mounted an electrogoniometer, as can see in figure. 13.

Fig. 13. Biometrics equipment mounted on the exoskeleton

The results, consisting of the joint angle variation in time are graphically presented in figure 12. Compared to the variation of human walking cycles, in the case of the exoskeleton it can be seen that the cycles vary slightly between them, being a cyclic movement of a robotic structure

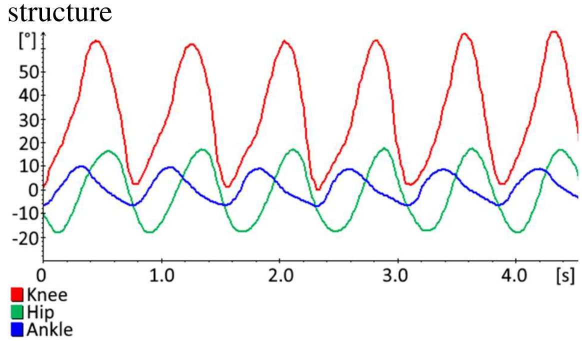


Fig. 14. Diagrams of experimental consecutive cycles of flexion-extension – exoskeleton

For each joint were determined the medium normalized gait cycle. In figures 15-17 is presented the medium normalized gait cycle of the exoskeleton joints: knee, hip and ankle.

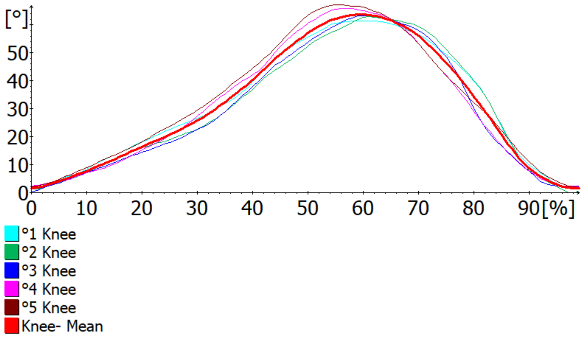


Fig. 15. Medium cycle of flexion- extension angle for the knee joint of exoskeleton

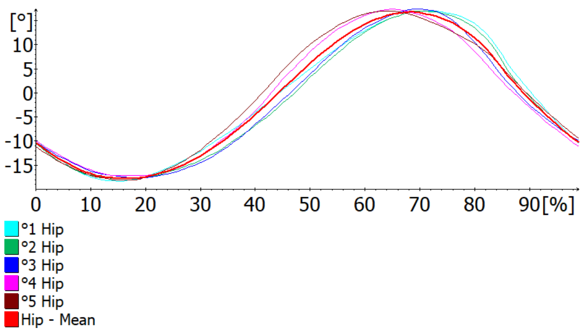


Fig. 16. Medium cycle of flexion- extension flexion angle for the hip joint of exoskeleton

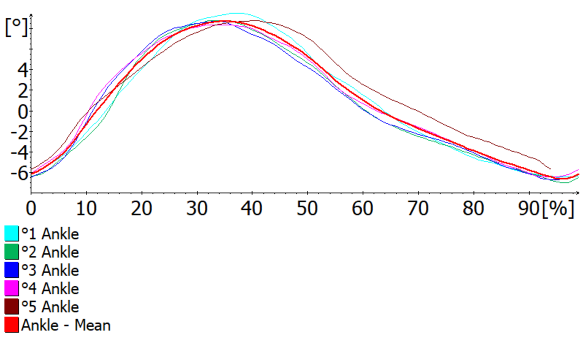


Fig. 17. Medium cycle of flexion- extension flexion angle for the ankle joint of exoskeleton

A comparative diagram between the normalized medium of the flexion-extension angle of the healthy, osteoarthritic knee until and after surgery and the normalized cycle of the flexion-extension angle of the exoskeleton's knee is presented in figure 18.

It can be seen from figure 18 that the knee extension of the exoskeleton is 12-15° larger than that of the OA knee, and in the first 50% of the cycle, the movement of the exoskeleton is similar to that of a healthy knee, much higher than that of the knee OA. In the case of the exoskeleton knee joint, the maximum angle reaches 63°. From the point of view of the shape of the curve, the two cycles show some differences given primarily by the lack, in the case of the exoskeleton, of the first loop of the middle cycle. Another difference is found in the position of the maximum points that do not coincide, the exoskeleton reaching the maximum value of the angle closer to the beginning of the cycle compared to the healthy subject.

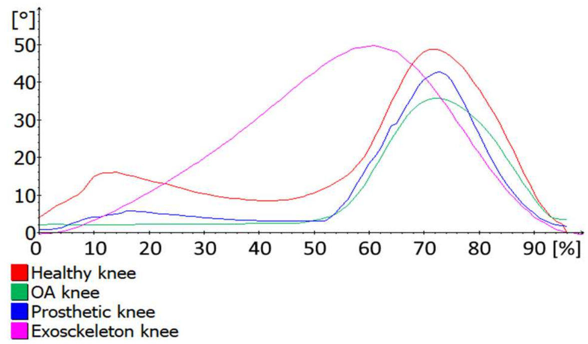


Fig. 18. Comparative normalized cycles for healthy knee, osteoarthritic knee, prosthetic knee and exoskeleton knee

Comparative graphs between the normalized medium cycles of the subjects' sample and of the exoskeleton were also obtained for the hip joints and presented in figure 19.

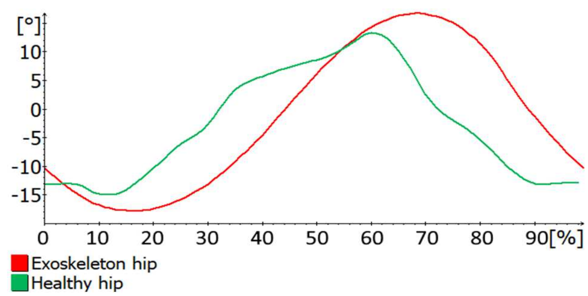


Fig. 19. Comparative normalized mean cycles for healthy hip and exoskeleton hip.

In the case of the medium cycle of the hip joint of the exoskeleton as in the case of the joint of the healthy subject, the angle has both positive and negative values, figure 17. There is a greater variation of the angle of the exoskeleton, between -18° and 17°, compared to the angle of the healthy subject which varies between -15° and 13°. The shape of the two curves is similar, but it has some differences, given the rigidity of the exoskeleton, so it is observed that the diagram of the exoskeleton does not show waves on the curve. In the case of the ankle joint, the shape of the medium cycles of the exoskeleton and the healthy subject differs, but, in terms of angle variation, the values are close, so in the case of the exoskeleton the angle varies between -7 ° and 9 ° and in the case of the healthy subject varies between -9° and 10°.

6. CONCLUSIONS

This article presents the virtual model and prototype of a proposed exoskeleton project used to assist the movement of human gait. Because it can maintain and improve the mobility of disabled patients, and can perform repetitive exercises, the exoskeleton can be easily used for medical rehabilitation. Performing appropriate rehabilitation exercises by adjusting the exercise level according to the patient's requirements is the main benefit of robotic rehabilitation.

Numerical gait analysis is performed using Maple software. A numerical simulation of the exoskeleton gait was performed to validate the functionality of the mechanism. The movement of the subjects, of the patients suffering from osteoarthritis of the knee, as well as that of the physical prototype of the exoskeleton were evaluated biomechanically using the Biometrics system. The results obtained are compared with the numerical results of the movement. Human walking is a repetitive movement, you can see changes from one step to another and from one subject to another. In our case, the extension movement of the exoskeleton's knee are 12-15° greater than the OA knee and that in the first 50 percent of the cycle, the exoskeleton performs a movement similar to that of the healthy knee, with much amplitude higher than the OA knee.

7. ACKNOWLEDGMENTS

This paper was supported by the Project no. 546/2020, code PN-III-P2-2.1-PED-2019-3022, entitled „ Innovative modular robotic system for medical recovery of brachial monoparesis - NeuroAssist” financed by UEFISCDI.

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PROIECTAREA ȘI EVALUAREA UNUI EXOSKELETON UTILIZAT PENTRU REABILITAREA GENUNCULUI OSTEOARTRITIC

Rezumat: Primul obiectiv al acestei lucrări este de a dezvolta modelul virtual și prototipul fizic al unui nou exoschelet, util pentru stabilizarea și reabilitarea genunchiului osteoartritic uman (OA). Al doilea obiectiv este validarea exoscheletului propus utilizând rezultate numerice și experimentale ale ciclului mediu de exoschelet. Un studiu experimental este furnizat pentru a compara amplitudinea și forma ciclurilor medii ale unghiurilor de flexie-extensie a genunchiului unui eșantion de opt subiecți sănătoși și un eșantion de șase pacienți cu genunchi OA, înainte și trei luni după înlocuirea totală a genunchiului.

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