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Wrist Exoskeleton Device with a Novel Cable Drive Solution

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ABSTRACT

This paper presents the design of a lower limb exoskeleton made for the purpose of wrist joint rehabilitation. The authors use the exoskeleton structure in order to cope with the user's upper-limb kinematics and to provide motion to the wrist joint when the arm is in any possible spatial configuration. To reduce the inertia of the mechanical structure, the motors are fixed at the back of the user and the power transmission is realized via a cable drive transmission. Two elastic cables are used to control the flexion/extension movement of the wrist joint. The tensions inside the elastic cables are controlled within the use of 2 torque sensors. By using two DC motors, the actuation unit can act like human tendons and provides more natural assistance motion. At the output axis, a third torque sensor is used to allow the control of the interaction between the mechanism and the user's wrist joint.

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1. Introduction

Today in Vietnam, stroke stands as a leading cause to both mortality and incapacitation. Reportedly, stroke incidence rate is around 0.16% for 2021 [1]. Survivors of stroke often contend with a loss of physical prowess and typically require therapeutic interventions to regain their mobility. Similarly, patients at ICU also suffer joint stiff after a long period of immobility, which is one of the main causes of upper limb/ lower limb impairment. Therefore, functional rehabilitation exercises developed for the post stroke / ICU patients is primordial in order to allow the patients to progressively regain normal functions of their sensorimotor system [2], [3].

Continuous passive motion exercises can be indicated at the early phases of rehabilitation to prevent joint stiff and maintain joint's range of motion [4], [5], [6] with similar results compared to exercises realized by professional therapy [7]. Today, exercises using knee CPM [8], [9] as well as upper-limb CPM [10], [11] or cycling devices [12], [13] were investigated by researchers. These devices generally provide passive motions (i.e. motion controlled in velocity, in open-loop or close-loop) to the targeted anatomical joints. Force control is generally not mentioned in CPM literature as these machines are generally used in early phases where the patients' joints are still so weak that resistive exercises are not required yet.

In this paper, the authors explore the possibility of using exoskeleton to realize rehabilitation exercises on patient's wrist joint. The system is composed of an exoskeletal structure and a cable drive system allowing the control of the targeted joint at distance. The use of torque sensors allows the programing of both passive and active exercises on the device [14].

Cable drive solutions enables the separation of the motors unit from the exoskeleton's mechanical frame by moving it to a fixed base, thus reducing the inertia of the mechanical frame. This solution also allows realizing force control using series-elasticity technique [15]. Flexible cables can be used instead of output springs, which at the same time provide a higher level of safety for the system.

Since 2000s, Bowden Cables systems were developed by researchers for active exoskeletons [16], [17]. Bowden Cable drive solution uses one single motor and two cables functioning in push-pull mode. The tensions inside the cables are controlled by the springs, which require a manual adjusting procedure before using. In addition, the dynamic performance of the system is defined by the motor, which in general provides a limited frequency band-width if powerful. Coupling a small motor to the principal one can help overcome this issue [18].

In this paper, the authors present a novel solution for the design of wrist exoskeleton using a cable drive system with 2 DC motors, that are controlled in torque via torque sensors. With this solution, the tensions inside the cables can be controlled. The output torque is generated by controlling the difference between the 2 cables tensions. The mechanical design was realized following the rules for exoskeleton design established in [19]. The system is controlled both in torque and in position. Control solution is presented in details and first experiments results are presented and discussed.

2. Materials and Methods

2.1. Cable drive solution

The cable drive solution [20] that is being used for our system includes 2 DC motors controlling separately the tensions of 2 flexible cables which are fixed onto the output axis (see figure 1). By setting the 2 tensions set-points at 2 different levels, one can control the output torque at the output axis. Three torque sensors were used: 2 for the control of the cables tensions and 1 at the output axis to control the interaction with the user.

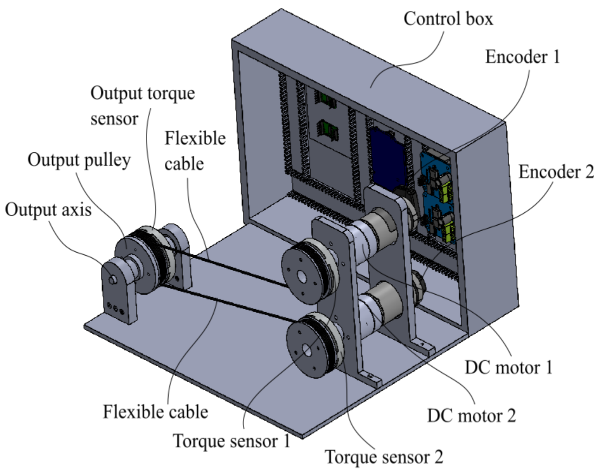

Figure 1. *Prototype of the cable-drive actuation unit [20].*

In our wrist exoskeleton design, the output axis is placed at the user's wrist level and the 2 motors are fixed on a base that is located at the user's back. This design allows to reduce the inertia of the whole system to a minimum value. Furthermore, the output axis can be nearly anywhere in space and is not necessarily parallel to the 2 motors' axes.

2.2. Wrist joint exoskeleton design

The design of the exoskeleton was realized follow the design rule established in [19] to create a "transparent mechanical system" that allows the user to naturally move the upper-limb, which is attached to the device, without feeling constraint by the mechanical system.

According to this rule, for the upper limb, the mechanism should be designed in following order: the shoulder joint part, followed by the elbow joint part, and finally the wrist joint part. Each part should be secured to user's limb, creating a kinematic loop. The degree of freedom of the kinematic loop (anatomical joint - mechanism) should be equal to 1, that allows the joint the move freely. Figure 2, 3 and 4 illustrates the design solutions for the shoulder, the elbow and the wrist joints.

Three successive rotational joints forming a mechanism in series is used at the shoulder level (see figure 2). The 3 axes are intersecting at one single centre of rotation to form an equivalence of spherical joint. Right after the 3rd rotational joint, a slider joint is added in order to support the attach mechanism connecting the structure to the user's upper arm.

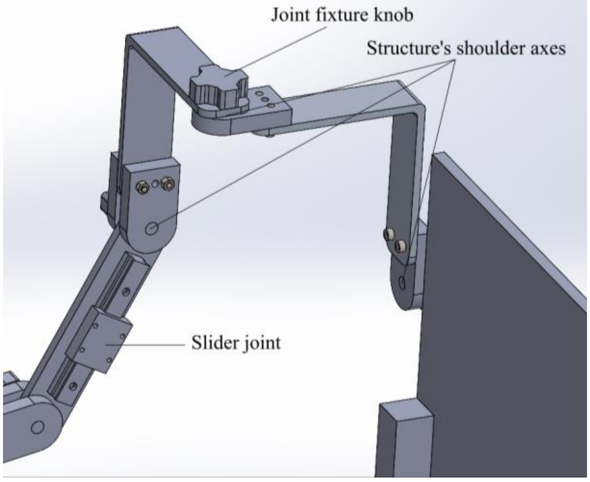

Figure 2. *Kinematic solution for the shoulder.*

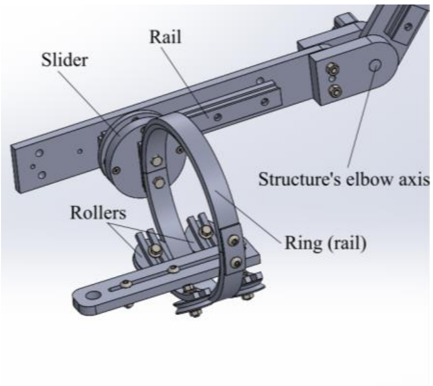

Figure 3. *Design solution for the elbow.*

At the elbow level, a rotational joint is used to create flexion/extension movement, follow by a slider joint that allow to adjust to the user's forearm length.

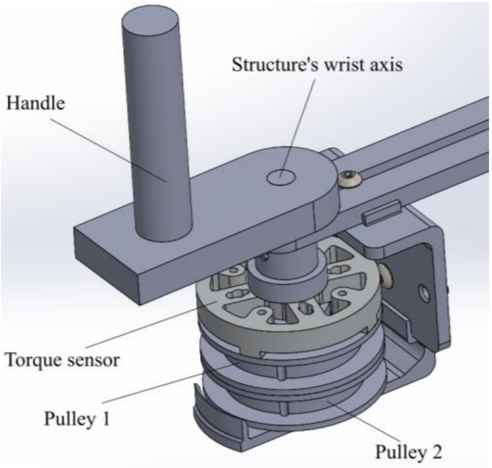

Figure 4. *Design solution for the wrist.*

The second rotational degree of freedom is composed by a rolling mechanism that produces motion on a circular rail. This solution allows to shift the axis of motion inside the circular rail, aligning it to the elbow's internal/external rotation axis (see figure 3).

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At the wrist level, one single axis of rotation is used, which is the actuated output axis. 2 pulleys are fixed at this output axis, that allow the fixation of the 2 flexible cables. A torque sensor, as well as a precision potentiometer are also placed at this same axis to measure the interactive torque and the displacement of the wrist joint.

Figure 5 illustrates the 3D design of the whole system. In this system, the actuation is realized at the wrist level. However, other anatomical joint (shoulder & elbow) can be easily actuated as well by simply introducing the system of torque sensor and pulleys at the targeted joints. We introduced a system of fixture knobs at the non-actuated joints to balance the mechanical structure's weight and to immobilize the exoskeletal structure when the exercises are being realized on the targeted joint (here is the wrist joint).

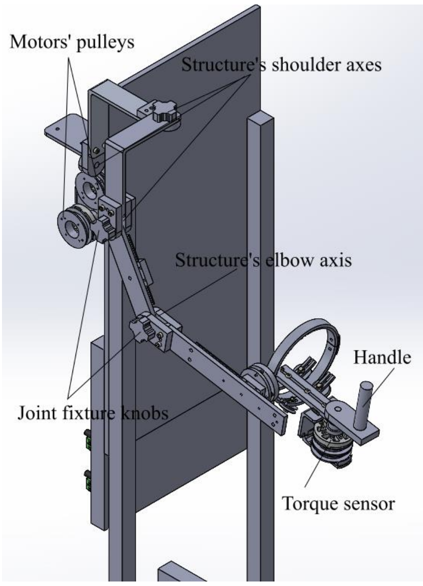

Figure 5. *3D CAD Model of the whole system.*

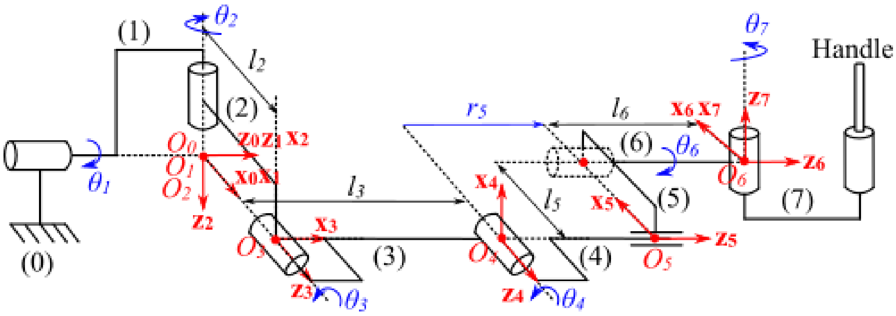

Figure 6. *Parameter setting of the upper-limb exoskeleton, using modified D.H. Notation.*

Table 1. *Modified D.H. parameters*

Matrix	α_i	a_i	θ_i	d_i
T_{01}	0	0	θ_1	0
T_{12}	$-\pi/2$	0	$\theta_2-\pi/2$	0
T_{23}	$-\pi/2$	0	θ_3	l_2
T_{34}	0	l_3	$\theta_4+\pi/2$	0
T_{45}	$\pi/2$	0	$-\pi/2$	r_5
T_{56}	0	l_5	θ_6	l_6
T_{67}	$-\pi/2$	0	θ_7	0

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The kinematic scheme of the whole system is shown in figure 6. The parameter setting is built using Modified D.H. Convention. The external structure of the system has in total 7 degrees of freedom which is equal to the d.o.f. of a human arm. The modified D.H. parameters are presented in table 1.

2.3. Control solution

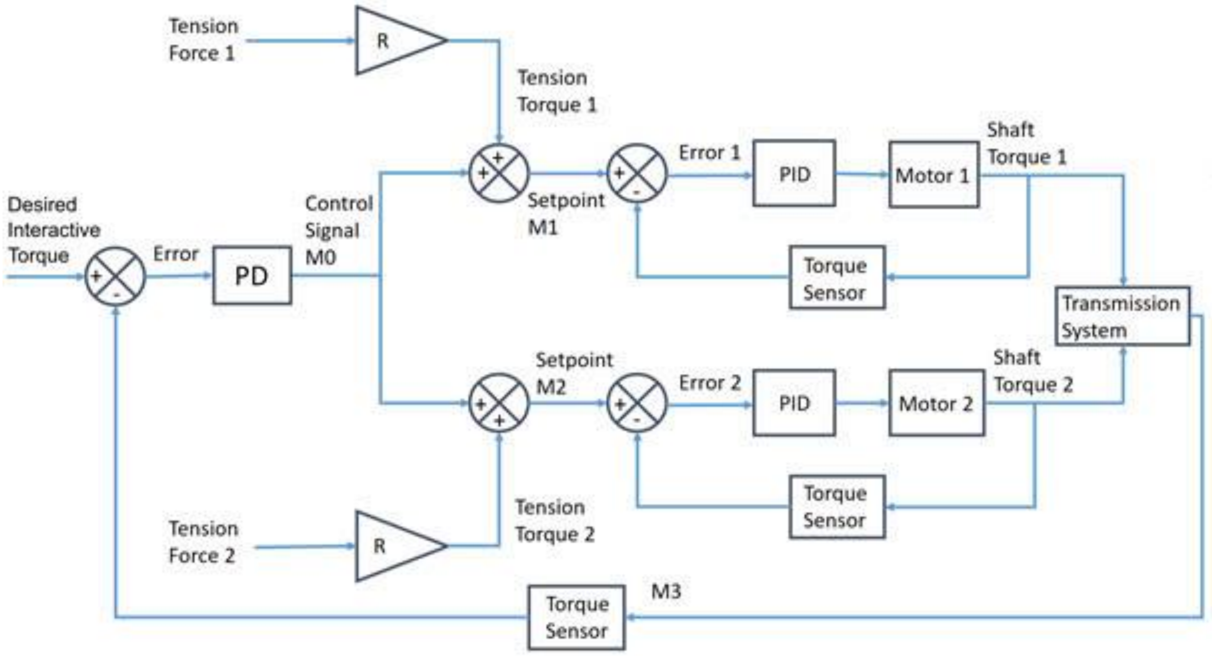


Figure 7. *The system control scheme*

Figure 7 illustrates the control solution of the system. The interactive torque M_3 is measured by the torque sensor fixed at the output axis $\mathbf{z}_7$. This measure is the feedback signal that allows the determination the torque set-point signal M_0 for the control of the 2 DC motors torques. M_0 is computed by a PD controller. The torque set-points M_1 and M_2 of the 2 DC motors can then be determined in function of M_0 using following formula:

$$\begin{cases} M_1 = \left(F_0 - \dfrac{M_0}{R_3} \right).R_1 \\ M_2 = \left(F_0 - \dfrac{M_0}{R_3} \right).R_2 \end{cases} \tag{1}$$

Here M_1 and M_2 are the torque set-points for the 2 DC motors. F_0 is the initial tension force inside the cables, that can be set by the operator and is controlled by the actuation units. Ri is the radius of the pulleys. In case that $R_1 = R_2 = R_3 = R$ (i.e. all the 3 pulleys, 2 at the 2 motors'axes and 1 at the wrist output axis, are similar), we have:

$$\begin{cases} M_1 = F_0.R + M_0 \\ M_2 = F_0.R - M_0 \end{cases} \tag{2}$$

When there is no interaction between the user and the system (M_3 = 0), the 2 torque set-points M_1 and M_2 are both equal to the torque value $F_0.R$ that generates the cable's tension. Only the tensions inside the cables are in control. Different operational modes can be defined for the system: Following mode (Zero Interactive torque), Resistive mode and Assistive mode. The first 2 modes can be realized using the law of impedance control [14], [21]-[23], modeled as follow:

$$T = -k.\theta - \mu\dot{\theta} \tag{3}$$

where T is the desired interactive torque set-point. k is the stiffness and μ is the viscous coefficient of the system which can be defined by the operator.

In Following mode, T is set to 0 (i.e. k=0 and μ=0). When the user has an intention of motion and apply a force onto the handle, the interactive torque is different from zero ($M_3 \neq 0$). This results in a difference in the values of M_1 and M_2 (according to equation (2)). This difference in torque generates a movement at the output axis, that follows the user's intention of motion. In Resistive mode, k or/and μ are different from 0. Therefore, the system reacts like a spring/damper model, providing memory force / viscous friction that resists to the user's movement.

To realize the active mode, a recognition algorithm has to be implemented to detect the wrist's phases of motion, and the system will provide the assistive torque precisely at one particular phase of motion.

3. Results and Discussion

Figure 8 presents the first prototype of the wrist exoskeleton. The motors unit as well as the control box are fixed at the back of the user. The 2 flexible cables are fixed at the motors' axes via 2 pulleys. 2 torque sensors are fixed to these 2 pulleys in order to measure the cables tension forces.

Figure 8. *Prototype of the wrist exoskeleton*

These 2 cables are connected to the output axis (axis $\mathbf{z}_7$). Another torque sensor is also fixed to this axis, allowing the measurement of the interactive torque M_3. The contact between the user's hand and the system is realized at the handle. The displacement of this handle is measured by a precision potentiometer fixed at $\mathbf{z}_7$. For other passive joints at the elbow and at the shoulder, we use fixture knobs to block them once the set-up procedure is done.

The passive mechanisms that connect the exoskeleton external structure to the upper limbs are designed following the principles described in [19], with the use passive joints to eliminate residual stress generated by the misalignment between the exoskeleton's mechanical principal axes and the human anatomical joint. Here, specifically, the mechanism PRR (1 slider – 1 universal joint) was added in between the link number (3) of the mechanism (Fig. 6) and the user's upper arm.

Two experiments were conducted. In the first experiment, the user was asked to move the wrist joint in flexion/extension repetitively and the system is controlled in such a way that it will follow the user's intention of motion by minimizing the interactive torque M_3. Before the experiment, a position calibration procedure was realized: the user was asked to keep his wrist joint straight to record the initial position. The desired interactive torque (torque set-point) is set to zero.

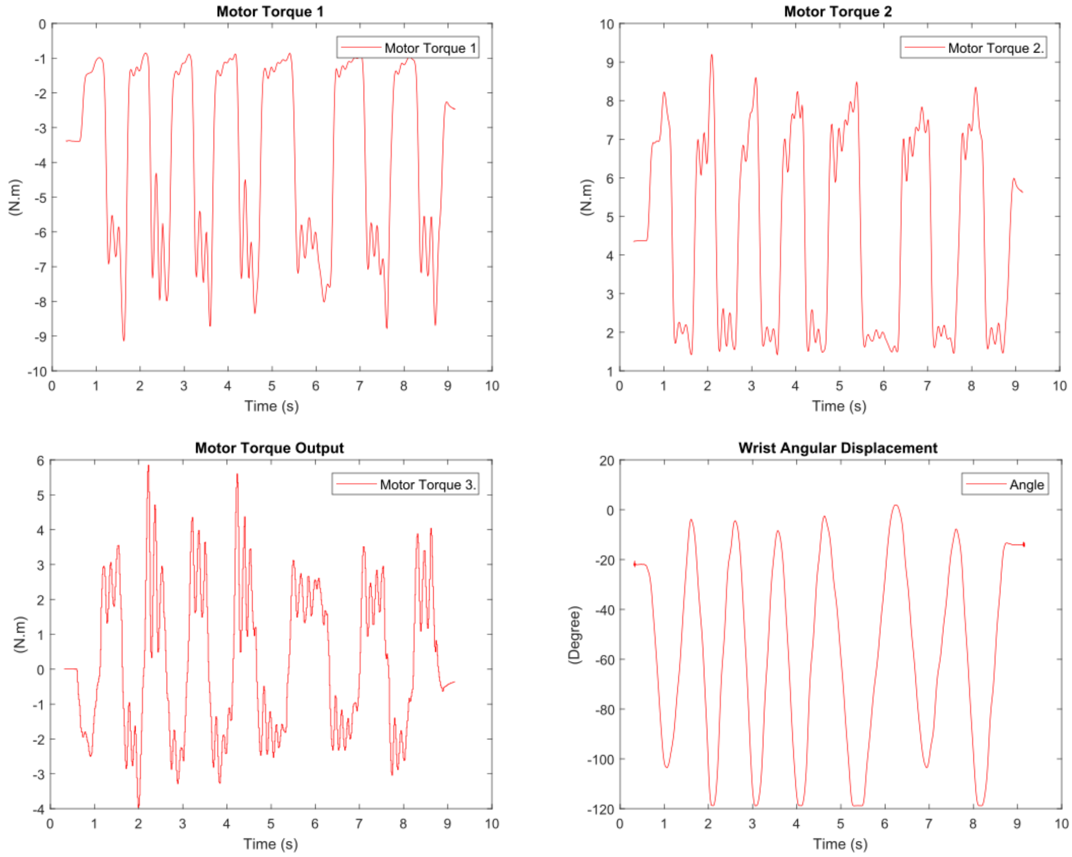
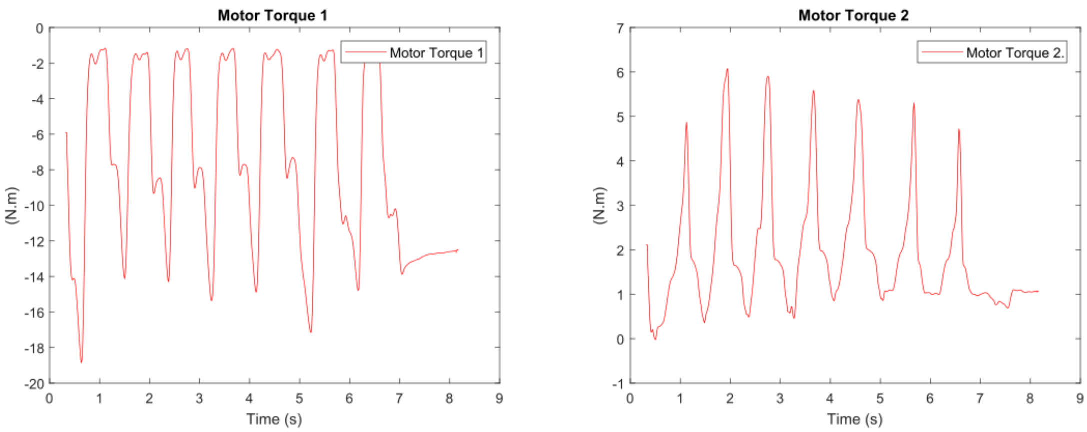


Figure 9. *Result of the 1st experiment: Following mode.*

Figure 9 represents the result of this test. One can see that the torque M_3 varies around the set-point value which is set to zero here. The interactive torque is maximum at reversal movements (Flexion to extension and vice versa).

In the 2nd experiment, the user was asked to resist to the motion of the output axis that is generated by the system during a certain time before forcing the system to come back to position zero. This back-and-forth movement was repeated several times. To generate the motion, one define the set-point of the torque controller at -5 N.m. Figure 10 shows the measurements of the 2 motors torques M_1, M_2 and the output interactive torque M_3 as well as the wrist joint angle measured by the precision potentiometer. As the resistance was set for one single direction, the resistive torque of motor 1 is more important than that of the motor 2. One can see here the interactive torque M_3 varies around its mean value -5 N.m.



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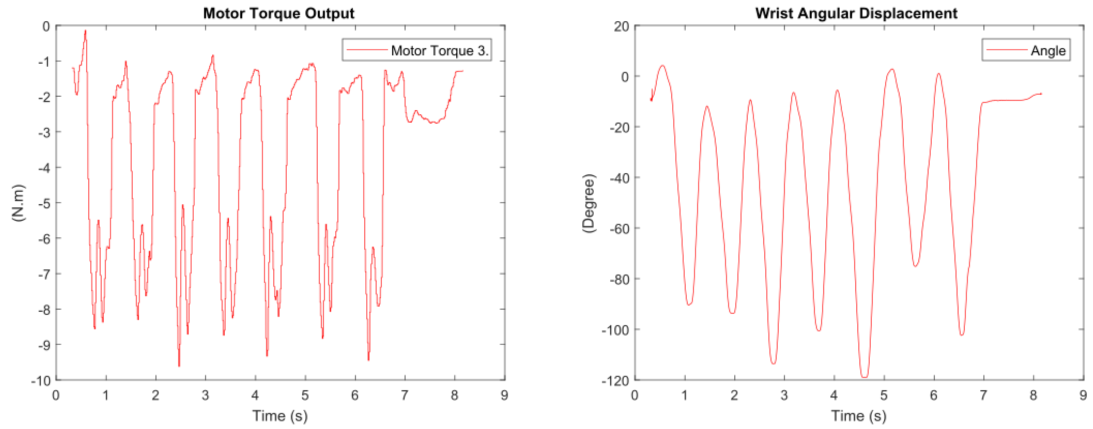

Figure 10. *Result of the 2nd experiment: Resistive mode.*

4. Conclusions

In this paper, an innovative design solution for active exoskeletons built for human anatomical joints functional rehabilitation purposes is presented. The mechanical design was realized by following the principle of self-alignment between human joints and mechanical linkage. Passive joints were added to free the constraints generating by the mechanical structure when connecting to the human limbs, thus assuring that the user can move his arm nearly naturally. A new cable drive, using 2 independent flexible cables to control one single torque output, was also used. The tensions inside the 2 cables are controlled via 2 DC motors and 2 torque sensors mounted onto the cables' pulleys. This approach allows the control of any joint at distance, while minimizing the inertia of the mechanical system by fixing the motors on a fixed platform. Here, the targeted joint is the wrist. A 3rd torque sensor is placed at the output wrist axis to realized different torque/position control modes for the joint. 2 control modes were tested successfully: User movement following mode and resistive mode. The assistive mode, that requires the implementation of an algorithm for the recognition of the wrist joint's motion phases will be subject of future work.

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Conflict of Interest

The authors declare no conflict of interest.

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