Rev. Roum. Sci. Techn.– Électrotechn. et Énerg.
Vol. **71**, *2*, pp. 335–340, Bucarest, 2026

A PROTOTYPE OF A DIRECT-DRIVEN ELBOW ORTHOSIS WITH HARD AND MYO ON/OFF CONTROL

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Keywords: Active orthosis; Upper limb; Elbow; Muscle electromyographic (EMG) signal; On/off control.

Elbow joint disorders occur after stroke and other neurological disorders, daily or sports traumas, etc. Rehabilitation with technical devices is a promising approach for helping these people return to normal life. To present an active wearable direct-driven elbow orthosis, ActElMO, and to conduct experiments with healthy subjects. The 3D-printed orthosis, with its anatomical design, is directly driven by an electrical actuator. The onset of elbow flexion can be set manually, without user effort, or via an electromyographic (EMG) signal from the biceps brachii (BIC) muscle. Experiments with 10 healthy subjects at various flexion velocities used this on/off EMG control, with individual thresholds set. The EMG signals from the muscles BIC and triceps brachii, and the elbow angle were recorded and processed. Different ways of EMG signal processing were tested. The chosen electrical motor provides sufficient power for rapid forearm movement with the orthosis. The device, including its trunk attachment, is user-friendly and convenient. The EMG signal from the BIC muscle is suitable for on/off control.

1. INTRODUCTION

Upper limb motions are very important for human daily activities. Problems with joint motions and muscle coordination can be due to traumatic incidents or neurological diseases of the central and peripheral nervous systems (stroke, multiple sclerosis, Parkinson's disease, neuroinfections, *etc*.). According to [1], neurological conditions were the leading cause of disability worldwide in 2021. The most common cerebrovascular disease, stroke, can cause limb damage, and it can persist in chronic hemiparesis [2]. Mainly, the elbow joint and fingers of one upper limb are affected [3]. Stroke is the second most common cause of mortality in the world [4] and takes the third place for disability-adjusted life [5].

After the acute phase of the disease, rehabilitation care becomes self-initiated. The patient must visit medical centers for rehabilitation or to engage individual physiotherapists, but not everyone can afford this. A home-based therapy with simple technical devices for rehabilitation could be a very useful decision [6]. Such devices can also be efficient for training older people to strengthen their weakened muscles [7].

Many technical devices (robots, exoskeletons, and orthoses) are reported in public media and scientific journals, but a small number of them are commercially available. The most well-known elbow commercial orthosis is MyoPro - arm and hand orthosis [8]. According to [9], other commercial systems are *Amadeo*, *CyberGrasp, Hand of Hope*, *InMotionHAND, etc*. Therefore, one inexpensive wearable technical device for elbow rehabilitation is missing. Below, we will concentrate mainly on such devices that use electrical driving systems.

There are good reviews for upper-extremity rehabilitation robots in [7, 10-12]. In [9], 11 technical devices having one degree of freedom (DOF) (flexion/extension in the elbow) are mentioned. Except for some uses, hydraulic or pneumatic actuators [13-15], all others use electrical driving. Using pneumatic or hydraulic driving systems requires air or liquid compression stations, so these technical devices cannot be portable. Today, many light and powerful electrical motors and batteries exist with a good proportion between power, size, and weight. The electric drive could be either a direct drive system [7] or an indirect one with a toothed belt reduction gear drive for increasing the torque [16,17]. With great regret, the authors of such papers rarely mention the type and the torque value of the electrical motor they use. Usually, MAXTON actuators are implemented [17,18]. It should be noted that elbow joint torque was reported to be up to 5.8 Nm during daily activities [15]. There exist advanced electrical drives - smart actuators with fully integrated DC Motor + Controller + Driver + Encoder + Reduction Gear + Network in one DC servo module. The information and commands between such an actuator and the master control unit are transmitted via a high-speed data link. Such devices may be used for an orthosis drive, and for additional safety, the maximum torque of the motor can be software limited.

The elbow flexion/extension motion is from 0^0 to 120^0 [10]. The current angle between the two arms of the rehabilitation device is important for setting individual angle limits for each patient and for the control system to use. It can be extracted by the encoder of the used actuator can extract it.

As to the mechanical construction, there are several important points. The first one is whether the mechanical links can be adjusted to be used by people of different sizes [19]. However, such a construction can violate mechanical stability. Another solution is to produce several orthoses. The second point is the number and type of DOF of an elbow orthosis. It can be one DOF (flexion/extension only) or 2 DOF – including also elbow pronation/supination. Including pronation/supination, the mechanical system will become more complex, but the adjustment between the axis of rotation in the natural elbow joint and the axis of rotation of the technical device will be more precise [2]. Another requirement for a mechanical system is to provide hard safety stoppers and places for electromechanical elements to ensure proper start and end values for the angle, which may be different for dissimilar patients. The discussion point is the weight of the orthosis. A reduction gear construction aiming to increase the joint torque adds extra weight. Direct drive is more suitable, but the electrical motor must have sufficient torque; the greater the torque, the heavier the device. Fortunately, in the present day, there exist powerful motors for robots and drones with small weights. Other details adding weight are the arms. Usually, they are produced from aluminum [7]. Light and complex details can be produced from plastic by 3D printers. When constructing two parts of an elbow orthosis (arm and forearm), attention must be paid to the special design ensuring the hard connection of these parts and, of course, the whole device to the human body – shoulder, grille, and trunk.

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DOI : 10.59277/RRST-EE.2026.2.28

The control algorithm of the orthosis may be hard or with myo-control (EMG) feedback. Hard control means that a computerized system controls the motor torque according to given laws for angle, angular velocity, *etc*. Thus, pre-given motion in the joint is performed without the participation of the patient. More modern myo-control is based on registered EMG signals from surface muscles (or intramuscular sensors, most often applied for prosthetic control [20]). The use of surface EMG signals is grounded in many papers [21–23]. It should be noted that EMG activity of the upper arm muscles is retained in most stroke survivors [24] and is strong enough to serve as control signals after suitable processing. It is stated that EMG signals directly reflect the user's motion intention and that cerebral plasticity plays an important role in motor recovery [25]. Hence, by motor learning, the brain can adjust to new situations due to some functional reorganization of the brain [26]. This phenomenon is known as neuronal plasticity [27] and is characterized by the ability of the brain to restructure itself by forming new neural connections. The registered EMG signals are amplified and filtered, and the RMS is calculated [22,28]. In some papers, only "flexors" and "extensors" are mentioned [7]; in others, the concrete muscles biceps brachii and triceps brachii are taken for driving an elbow orthosis [18,29,30]. Some authors use EMG envelopes [31], others use neuro-fuzzy control [28, 32]. When using suitable processed surface EMG, two main approaches for orthoses control exist – on-off [12, 29] and proportional [13, 33]. For on-off control, a specific EMG signal threshold must be set; when the signal exceeds it, the motor starts operating at constant velocity. For proportional control, the envelope curve is calculated from the raw EMG signal, and the control signal is proportional to it.

The paper presents a wearable elbow orthosis, ActElMO, directly driven by an electrical motor, and its two control modes: hard (automatic) and myo (using a processed EMG signal from the biceps brachii).

2. METHODS

2.1 MECHANICAL DESIGN OF THE ORTHOSIS

The mechanical construction consists of two main parts designed ergonomically by using a CAD program.

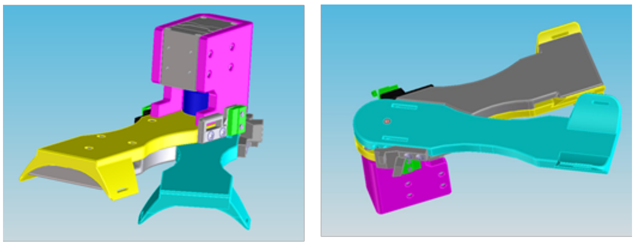

Fig. 1 – 3D views of the orthosis created by using a CAD program.

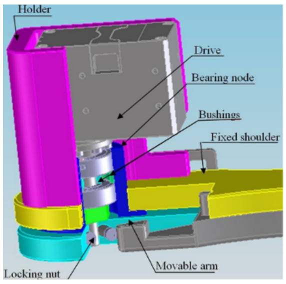

Fig 2 – Bearing the orthosis.

Fig. 3 – Photos of the orthosis attached to the shoulder griddle. The attached EMG electrodes are also visible in the right photos.

The lengths of the arm and forearm of the orthosis are chosen according to the mean values of human upper limb segments [33]. Their lengths are 241.6 mm for the arm and 229.5 mm for the forearm. The weights of the two parts are 227 g for the arm and 203g for the forearm (for example, the weight of the exoskeleton in [22] is 5 kg). There is no option to adjust the current arm lengths according to the individual subject sizes. There are specially made holes (Fig. 1) in the arm and forearm for belts that fasten the forearm to the wrist, and the arm to the shoulder and trunk (Fig. 2). The third part is a holder (carrier) for a DC motor. These parts are 3D-printed using PLA filament (Fig. 3). Security is achieved through built-in rigid supports.

A direct drive is used. The chosen actuator is Dynamixel XM540-W270-T. Its primary technical data are: power supply: 10.0–14.8 V; stall torque: 10.6 Nm (12.0 V, 4.4 A); weight: 165 g; no-load speed: 30 rpm (12.0 V); and absolute encoder: 12 bit.

2.2 CONTROL SYSTEM

The orthosis is controlled by a hierarchical three-level control system with EMG feedback. The main requirements for such a system are [35]:

- Safe-for-health voltages and currents;
- Additional safety of mechanics;
- Sufficient torque;
- Suitable dimensions and weight;
- Real-time motion PID control;
- Easy access to orthosis position, speed, current, and other system parameters;
- A wide set of drive and operating modes;
- Precise control is possible in different modes.
- The lower level of the control system is an electrical integrated actuator, the Dynamixel XM540-W270-T, referred to below as "servo" [36]. The purpose of the servo is to drive the mechanics of the orthosis by the motion law chosen. It should be noted that, for additional patient safety, the torque (current) was software limited.

- The middle level of the control system is an OpenCM 9.04 microcontroller [37]. The purpose of this level is: a) to communicate with the upper level for programming and data transfer, and b) to control the servo. It is available with the Arduino IDE, which offers API functions sufficient for lower-level control.
- The upper level is a personal computer (laptop) running the Arduino IDE [38] with appropriate libraries installed. It serves for OpenCM 9.04 programming and the user interface (UI). UI may also be realized by any Windows/Linux/Android, *etc*., terminal application or by a stand-alone human-machine interface.
- The EMG sensor used is the Myoware 2.0 muscle sensor from Advancer Technologies, LLC [39]. It measures muscle activity by detecting the electrical potential at the surface of the muscle, commonly known as surface electromyography.

2.3 EXPERIMENTAL SETUP

Ten healthy subjects participated in the experiments – 6 men and 4 women (mean age 41±7). The Scientific Council of the Institute approved the experimental procedure. The volunteers have no neurological or musculoskeletal disorders. They were informed in detail about the experimental procedure, filled out injury cards, and gave informed consent. The experiments aimed to check the effort caused by the orthosis to the trunk, the comfort of the human when using it, and the EMG signals of two surface muscles (m. biceps brachii -BIC and m.triceps brachii -TRI) performing flexion and extension in the sagittal plane with three different velocities. The EMG signals were recorded using triangular muscle sensors Myoware 2.0 placed above the belly of the muscles according to the recommendations on the web page http://www.seniam.org/.

The subject sits in a chair without armrests with feet placed firmly on the floor. Places where the electrodes will be attached are marked and cleaned with alcohol. The electrodes are attached above the BIC, TRI, and the reference electrode is attached to the acromial process. The electrodes click into the specified positions on the Myoware 2.0 sensors and are oriented according to mid and end positions in line with the muscle fibers. The subject's upper limb with an orthosis attached dropped down, and the cables were connected to a laptop without an internet connection and powered by a battery (to avoid additional noise). The orthosis is placed on the left hand with the help of the examiner so that the axis of the orthosis coincides with the rotation axis in the elbow joint.

Additionally, two participants underwent the same experimental procedure again, but the signal was taken only from the biceps brachii muscle because it is used for myo-control. The aim was to record both the raw signal and the envelope produced by the sensor, and the processed signal generated by our program using different methods.

The experimental procedure was as follows.

The subject sits on a chair, with upper limbs relaxed beside the body. The extension of the left hand is limited by the mechanical stoppers' orthosis, about 10^0. From this starting position, the following movements are performed:

1. Flexion-rest-extension to full ranges without motor working. The aim was to record the muscles' EMG signals to see the efforts due to the presence of the technical device. Three cycles of flexion, hold in the final upper position, and extension are performed. Each movement is performed for a period of 6, 3, and 2 seconds, and the upper positions are held for 1 s.
2. Flexion – rest – extension powered fully by the motor (compulsory rotation of the forearm) without the participation of the examined person. Three cycles of flexion, hold in the final upper position, and extension defined by the actuator are performed. Each movement is performed for 6 s, and the positions are held for 1 s. The starting and ending positions of movement in the elbow are from 10^0 to 135^0.
3. The experimental setup is the same, but the movements are performed for 3 seconds. The holding time of the positions remains unchanged at 1 s.
4. The experimental setup is the same, but the movements are performed for 1.5 s. The holding time of the positions remains unchanged.
5. Flexion – rest – extension initiated by biceps EMG signal and powered by the motor (myo-control). Three cycles of flexion, hold in the final upper position, and extension are performed. Each movement is performed for 6 seconds, and the upper positions are held for 1 s. However, to perform each of the 3 flexion-rest-extension cycles, there must be an incoming signal from the BIC that exceeds a previously limiting threshold, specific to each person.
6. The same as point 1, but the beginning of the motion flexion starts after the processed EMG signal of BIC exceeds a threshold. This threshold is initially determined by several attempts and fixed in the program.
7. The same as point 2, but the motion flexion begins after the processed EMG signal of BIC exceeds a threshold. The threshold remains the same.
8. The same as point 3, but the motion flexion begins after the processed EMG signal of BIC exceeds a threshold. The threshold remains the same.

After the experiments, all participants completed a questionnaire assessing the orthosis's functionality and any difficulties they experienced during use.

2.4 PROCESSING OF THE EXPERIMENTAL DATA

The processing of the numerical raw signal from the sensor is performed as follows (Fig.4):

- The digitization of raw sensor signals is accomplished using the built-in analog-to-digital converter (ADC) of the OpenCM-9.04 microcontroller. This microcontroller features a multi-channel ADC capable of 12-bit resolution. We utilize two of these channels for our application to process signals from the biceps and triceps. Each signal is sampled at 1000 Hz with 12-bit resolution to ensure precise measurement.
- Given that the signals we are measuring are bipolar, but the ADC operates on a unipolar basis, this introduces a DC component to the input signal. To mitigate this, we digitally process the signal by subtracting a fixed constant from each sample. This constant is determined through a preliminary calibration process, ensuring effective removal of the DC bias.
- The next step is calculating the root-mean-square value of the signal using 64 points (samples). This operation estimates the signal energy and filters sharp changes in the signal amplitude. Then, additional filtration is performed on the signal using a moving-average filter (8 samples) of the obtained RMS values. It helps to smooth the signal and increases the system's noise resistance.

- The values obtained in the previous steps are used to activate the orthosis by applying a threshold detector. We set the activation level manually depending on the signal strength. In future implementations, it is possible to use the proportional activation method and automatic gain control (AGC).

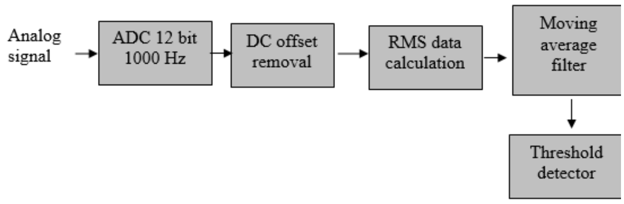

Fig. 4 – Digital signal processing. ADC – analog-to-digital converter; DC – direct current.

3. RESULTS

The main parameters achieved with the current mechanics and control system are a) torque 10.6 N·m, b) speed 30 rpm, and c) accuracy < 2 deg.

The raw EMG signals from the muscles BIC and TRI from the two sensors, as well as the processed signals and the angle between the arm and forearm taken from the encoder of the motor, were recorded (Fig. 5).

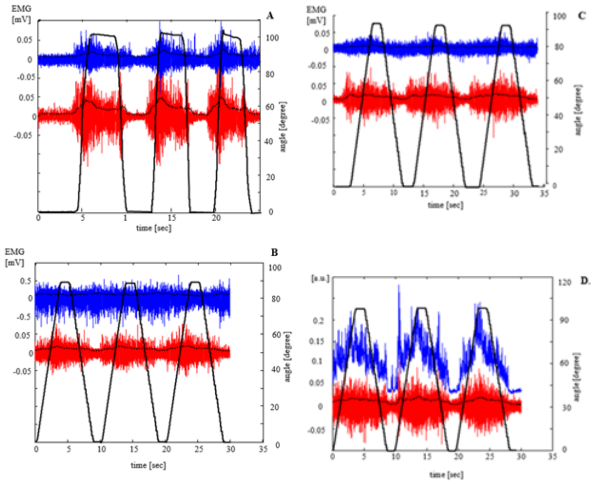

Fig. 5 – Raw EMG signals, processed EMG signals, and angle in the elbow joint for four motor tasks. **a.** Free motion without an active actuator. Blue and black – raw EMG signal of TRI and BIC, respectively, black dashed line – processed EMGs for the respective muscles, black continuous – joint angle. **b.** Hard control. Blue and black – raw EMG signal of TRI and BIC, respectively; black dashed line – processed EMGs for the respective muscles; black continuous line – joint angle. **c.** "myo" control. Blue and black – raw EMG signal of TRI and BIC, respectively; black dashed line – processed EMGs for the respective muscles; black continuous line – joint angle. **d**. Comparison between our processed signal and the envelope recorded from the myo sensor from BIC. Hard control. Red – raw BIC EMG signal, black dashed – processed EMG signal of TRI using our program; blue – envelope recorded from the used sensor (for better view, this curve is shifted up by 0.05 n.u.), black line – angle in the joint.

In Fig. 5a, the subject performs three motor tasks: flexion, rest, and extension. The actuator is not active. The aim is to assess the two muscles' activity when the subject wears the orthosis. Both muscles are active; BIC is more active, but both activities are comparable. During rest in the bottom positions, the activity of the muscles is less than in the upper rest position. All 10 participants performed these motor tasks. They did not report difficulties in wearing and carrying the orthosis. The activities of both muscles increase during flexion, which is slightly surprising for the extensor muscle TRI. In Fig. 5b the motion is fully automatic (hard control). The actuator does everything. The three tasks, flexion-rest-extension, are programmed by the controller and performed by the actuator. There exist activities of both muscles, but they are less in comparison with Fig. 5a. In Fig. 5c, the control is "myo" using the EMG signal of muscle BIC. The subject strengthens this muscle until some threshold is reached. This threshold is experimentally obtained. After that, the flexion-rest-extension task is automatically done by the actuator. Three attempts were performed for each subject. It should be noted that the thresholds for different subjects varied.

In Fig. 5d, the results from the last experiment with one of the two subjects with only the BIC EMG signal recording are shown. The task is "hard control, i.e., the motor task is automatically performed by the actuator. The aim was to compare the non-processed surface EMG signal from muscle BIC, the envelope produced by the sensor, and the signal processed by our own program. The envelope (blue line in Fig. 5d) is very noisy but follows the raw signal. Our processed signal (black line in Fig. 5d) is very smooth and is more suitable for use when "myo" control is developed, especially for further proportional control.

The general view of the field by the participant's questionnaire shows the following: the participants do not report any inconvenience using the orthosis; the orthosis is not very heavy and can be carried without problems; they think that it is possible to wear the orthosis without help from another person; they do not afraid from using EMG sensor; they feel some problems with justification between the axis of the orthosis and natural elbow axis of flexion/extension.

4. DISCUSSION

The orthosis is light (0.67 kg with the actuator and 0.5 kg without the actuator), regardless of whether direct electrical driving is used. The power of the motor is big enough to have a torque sufficient to move the forearm and orthosis even for big-size subjects – we made sample experiments with one 120 kg man. The way of fixing the orthosis to the shoulder and trunk is reliable. The experimental subjects report no problems. They report only light resistance in some positions of the elbow, which is probably due to the coaxiality between the natural elbow axis and orthosis axis (see videos on the web page https://biomed.bas.bg/bg/structure/motor-control/). Hence, this is an effect of only one DOF of the developed device.

The motor control according to the set by the computer program law is precise. The previously set elbow angle as a function of time is precisely followed.

Our observations suggested that the triangular EMG sensors are easy to use, but we encountered some issues during the experiments. The signal was unstable in some tests, and an unknown noise occasionally appeared. More information must be provided by the producer on how the envelope signal from the sensors is obtained and what filtration and amplification are used. Based on our measurements, the envelope shows many peaks (Fig. 5d), and the signal needs to be smoother to serve as a control signal. Our processing algorithm, based on the RMS level, gives a smooth enough signal (Fig. 5d) that can be used even for proportional control. The calculations for obtaining this signal are straightforward and can be performed in real time by a currently available microcontroller. That is why we used our processed signal (which can also be considered an "envelope" curve) rather than the envelope output from the sensors.

According to our experiments (Fig. 5a,b,c), the EMG signal of the muscle TRI is not suitable to be used as a control parameter. In most cases, it changes little with elbow flexion and extension. This is a slightly unexpected fact, since this muscle is an extensor and must be active during the extension phase of the movement. This probably does not happen, since the extension in the sagittal plane is mostly due to gravity, and flexor BIC activity is necessary to prevent rapid downward movement of the forearm.

Our observations during experiments with a myo-control suggest that the thresholds at which the orthosis starts to move automatically differ across subjects and must be set by the program individually. This obstacle must be resolved in the future so that patients can set this threshold themselves. This individuality is due to many factors: different sizes of the muscle BIC; different skin resistances; different positions of the sensor relative to the muscle belly; the influence of the conductive gel used, etc.

Strong and noise-free signals must be obtained from the controlling muscles to achieve smooth control of the elbow orthosis. It is important to accurately interpret the strength and timing of muscle contractions. There are several challenges in using the EMG signal from the triceps brachii for orthosis control. The TRI is a large extensor muscle, but the signal strength from its parts can vary depending on the level and type of muscle contraction. For example, the authors in [40] found unexpected muscle activation when investigating elbow activity patterns of five muscles. When the elbow extends in a supinated position, in addition to TRI, its antagonist BIC is highly active. The literature shows that biceps function is related to elbow flexion and plays no mechanical role in generating extension torque. Authors consider that inter-muscle activity depends on the situation. Furthermore, authors in [41] (2024) using ICrA correlation analysis detect triceps–biceps interactions in positive consonance during the opposite movement (elbow flexion) when only the BIC is engaged.

5. **CONCLUSION**

The mechanical parts of the orthosis are ergonomically designed by a CAD program and printed using a 3D printer. Thus, they can be adjusted for different user sizes by simply changing the models in the CAD program. They are printed using plastic filament. Thus, we achieve a lower weight while maintaining sufficient hardness in the components.

The direct-drive mechanism eliminates the need for reduction gears, which significantly reduces the device's weight. Thanks to the availability of powerful yet compact actuators, the orthosis itself is both lightweight and compact.

The presented prototype of the orthosis with its hierarchical three-level control system has been tested on real subjects. Tests were conducted in both no-feedback (hard control) and feedback (myo) modes. In the second type of test, the movement cycle was initiated after a threshold value of the processed EMG signal of m. BIC was reached (on-off control). The tests have demonstrated sufficient functionality and ease of use of the orthosis. The future work on the control system of the orthosis is mainly pointed in three directions:

- Development of a graphic interface for the parameterization of the rehabilitation procedures and their autonomous use by the patients at home;
- Using wireless communication (*i.e.*, Bluetooth) between the high control level and the local orthosis controller;
- Instead of the above-mentioned middle control level, a microcontroller with a digital keyboard and display, mechanically and electrically integrated into the orthosis, is to be used. It will provide more options and make using the orthosis easier for patients. This microcontroller will eliminate the need to visualize the upper level when the patient is working with the orthosis at home.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

SILVIJA ANGELOVA: Conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization, supervision, project administration, funding acquisition.

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PLAMEN RAYKOV: Visualization, resources.

EMIL PETROV: Software, investigation, data curation, writing—original draft preparation, writing—review and editing, visualization.

YASEN PAUNSKI: Methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization.

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