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Anomaly Detection of ESWT Device Supported by AI Agent Using Phase Portraits of Ballistic Pendulum*

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Abstract

One of the known physiotherapeutic treatment is extracorporeal shockwave therapy. It lets restore health and the comfort of life. These treatments require the usage of the specialised devices generating shockwave. As each device equipped with mechanical elements it is exposed to defects and operational wear. The objective of the service points repairing these devices is anomaly detection and their repair. Currently the diagnostic of these devices is done in hand and it requires a considerable amount of work. Following the world's trends in industry with the aim of automation of every process and supporting the AI agents, in this paper the cutting-edge method of measurement of the shockwave energy and AI model that recognises devices were presented.

Keywords: shockwave, ESWT, Charpy impact test, pendulum, machine learning, time series recognition

Introduction

Taking care of the physical state and comfort of life is possible thanks to the cornucopia of sometimes even sophisticated physiotherapy treatments. Among these ones, there is one more well-known and still developed: extracorporeal shockwave therapy (acronym ESWT). Thus, it is a patient-friendly therapy because it is non-invasively and drug-free. It allows to heal the part of the patient's body affected by disease or some structural alterations (e.g. lateral epicondylitis, calcaneal spur). The idea of this therapy utilizes injection of the acoustic wave into patient, generated by device - apparatus. Such wave penetrates into inside of the tissue (3-12 cm) and employs locally pathological tissue e.g. fragmenting calcific deposits and stimulating repairing processes of the body. There are many physical phenomena such as the mechanical impact effect, Hopkins' effect, cavitations shown by Császár et al (2015), microjets and so on. The details of these phenomena which can be observed are described in papers Sawicki et al (2022) and Loske (2017). It is worth to mention that the most updated unconventional applications of this therapy are discovered among others in esthetic medicine, veterinary and

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dental treatment. The source of shockwaves is apparatus - medical device. Sometimes it is so called the generator of the waves. Many varieties of solutions of the same apparatus can be found on the market.

Nevertheless, generalising their construction they can be divided into:

a) pneumatic devices,
b) electromagnetic devices.

The way that the waves are generated was the criteria of this classification. In the case of pneumatic devices as the name suggests, the potential energy of compressed air is transformed into shockwave energy. Analogically, electrical energy is changed into shockwave energy in electromagnetic solutions. Without discussing the details which can be found in papers Sawicki et al (2022) and Loske (2017) conversion of these energies conducted in a stepwise manner. For example, the potential energy of compressed air is transformed into the kinetic energy of moveable elements of the devices and this one into shockwave energy. The ESWT apparatus classically consists of two units: a driver/generator and an applicator. The physiotherapist operating this applicator injects shockwave into operated tissue. The element of the applicator which is exposed into direct contact with the patient's body is a transmitter. The front of the transmitter can have different shapes thanks to it is possible to generate waves of dissimilar geometrics (acupunctural, radial, focused) and the depth of penetration.

Transmitter as the other mechanical items of the applicator are used during utilisations. Hence, the aim is to measure energy of formed shockwaves. Such measure would help service points of these devices in diagnostic, anomalies detection and their repair. In many researches study by Sawicki et al (2022) and Reinhardt et al (2021) many methods of measuring the shockwave energy can be found, mainly there are:

- measure the vibrations of the transmitter with the usage of piezoelectric sensors, accelerometers,
- register shockwaves in a water medium using hydrophone.

What joins these methods is the possibility to precisely measure the shockwave. Moreover, the first of these methods allows to observe shockwaves generated with the higher frequency. During physiotherapists a treatment the frequencies 1-20 Hz (sometimes up to 22 Hz) are set. It was found that when this frequency was becoming higher and higher new problems occurred such as overlapping vibrations of the mechanical items of the applicator, shown in papers by Sawicki et al (2022) and Reinhardt et al (2021). Registering shockwave in 3D space in a water medium is the subject of Sawicki et al (2022) patent application.

Author's contribution.

Measurement-allowing experiments assume that the applicator is mounted permanently in the measuring instrument. It is an inconvenience from the point of view of the service points because this instrument should be insensitive to the way of applicator's mounting. In case of the measurement of vibrations it was essential each detail of mounting i.e. distances, sensor contact force. For hydrophone measurement it was vital precise setting of distance between transmitter surface and a sensor. Moreover, in case of electromagnetic solution there was a danger in contact with the electric applicator with the water (then special rubber caps are used).

To sum up, service points are looking for the fast, unsophisticated and insensitive to the precision of calibration of the method of ESWT measurement. The author inspired by Charpy impact test (co called Charpy hammer) and ballistic pendulum, described by Milutinović et al (2019), suggests the usage of pendulum for the rough energy measurement. This instrument would be so called phantom pretending to be equivalent of the operated tissue. It does not require in vivo experiments. The measurement itself might be insufficient for the diagnostics quit complicated devices because it would be worth to register the dynamic behaviour of this device. Thus, it is suggested to register a state-space plot (a phase portrait) of pendulum accelerated by shockwaves.

Manual analysis of the phase portraits would be required for serviceman's specialised knowledge and skills. Hence, following the cutting-edge trends it should be automatised this process with the support of the AI agent. This work is the later-day researches about designing AI agent supporting the process of ESWT device anomaly detection. Shown measurement instrument lets register a set of phase portraits which would be a training set for AI.

This paper's aim is to present the method of the shockwave energy measurement and recommend a new AI application in diagnostic of apparatus for this therapy. Using pendulum for ESWT energy measurement and using AI to support results' (phase portraits) analysis are the innovative solution so far not known in the literature.

Methodology

Testing environment

The energy measurement test bench (a measurement instrument) was constructed on the basis of a model of Charpy hammer. In the Fig.1 3D model of this measurement test bench is shown. Metal frame (a two-column frame) base was rigidly mounted to the floor. In this frame the moveable pendulum was hanged on the shaft. Pendulum's shaft rotated in plain bearings (for the calculations the fact of existing friction was omitted). The pendulum was equipped with a bob (350 g) in the shape of hammer's head which was hanged on using a stiff rod (0,3 m). Thanks to it pendulum moved only in one plane. Amplitude was measured by means of inclinometer built on the basis of encoder which counted rotates a gear set driven by the pendulum's shaft.

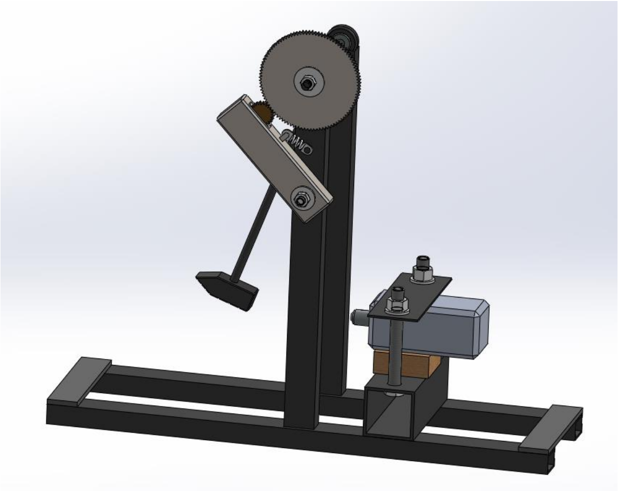

Fig 1. 3D model of the measurement instrument

Frame besides from aforementioned pendulum was equipped with a handle built on the pattern of the tool post. It allowed for a rigid assembly of the applicator in a frame. Applicator was mounted in such a way in order to the front of transmitter which was in contact with a hammer butt which was situated in the position of equilibrium. Then, it posed a zero kinetic energy and the lowest potential energy. During the mounting of the applicator it was necessary to try to coincide the tangent plane to transmitter surface and a butt plane. A line normal to a butt plane should be parallel to the radius of a spherical segment which was equivalent to transmitter head.

During trials it was tried to improve the acoustic impedance between transmitter and hammer using a gum membrane. The coupling fluid means were also used such as ultrasound gel.

It is also worth to say that author tried different methods of measuring the pendulum movement. For example, it was tried to equip hammer into the linear accelerometer which measured the acceleration of the hammer. Unfortunately, due to enormous internal stress vibrations which were in the pendulum bob after inelastic collision the measurements were disturbed. Acceleration measured by the sensor consisted of not only expected the acceleration of the pendulum, but also the internal vibrations. It was decided then not to install a sensor at the end of the hammer. The shaft rotations were measured. Furthermore, to increase measurement resolution the gear set was used (the gear ratio equalled 4) to transmit a shaft rotation to encoder shaft.

Because of two reasons optical version of the sensor was chosen. Firstly, in order to avoid the need of elimination of the bouncing phenomenon. Secondly, when an evaluation version of the applicator (i.e. without a metal case – EMF shielding) was tested electromagnetic disturbances can be inducted in a metal frame. Optical sensor was a galvanic isolation protecting measuring computer against the disturbances.

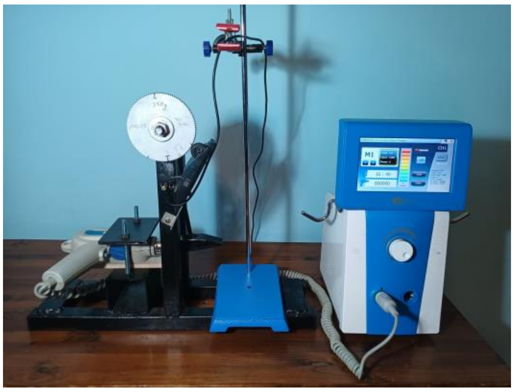

Fig 2. Measurement test bench

Encoder equipped with microcontroller which was connected to the PC via USB interface and was accessible in OS as USB device (HID class). In fact, disassembled computer mouse was used and it played role as an optical encoder. A special software was implemented in Python letting register the encoder rotations with timestamps (in microseconds). The number of counts per one degree of the angle was measured and the software calculation was calibrated. Thus, it is possible to simulate the pendulum motion, i.e. amplitude in the discrete moments. In the Fig.2 there is a photo of the real instrument constructed on the basis of 3D model from Fig.1.

Mathematical Model

As it was mentioned at the beginning of this paper the task of constructed measurement instrument was the evaluation of kinetic energy and dynamic transmitter work in an applicator.

In paper by Sawicki et al (2022) mathematical model was shown using the elements of Newton dynamics describing relation between the transmitter kinetic energy from apparatus work parameter such as the air pressure or the solenoid electric current.

Here one should proceed in the opposite way, i.e. evaluate transmitter kinetic energy on the basis of measured pendulum amplitude. To simplify analysis physical pendulum model was assumed.

Thus, the pendulum amplitude θ is measured during the experiments. Without usage of the small-angle approximation relation of the pendulum kinetic energy from amplitude is (as shown by Milutinović et al (2019)):

$$E_k(\theta) = mgl(1 - cos\theta) \qquad (1)$$

where: g - standard gravity,

l - the length of the pendulum (the distance between the shaft axis and the centre of bob mass),

m - bob mass.

Thus, it is possible to evaluate the kinetic energy of the hammer. Debatable is how ESWT energy is transferred to the pendulum. In ideal situation elastic collision occurred and due to the law of the conservation of energy whole ESWT energy should be transferred to the pendulum. However, in real conditions such collision did not occur. At the moment of shockwave generation in the transmitter case elastomer which stabilizes transmitter was compressed. A minimal transmitter displacement occurred. It was modelled in paper by Sawicki et al (2022) using a spring. In another Sawicki (2022) research this displacement was evaluated using FEM method. Thus, in reality inelastic collision occurs and it is possible to evaluated only the supremum of transmitter kinetic energy:

$$E_k \leq E_{ESWT} - E_{heat} \qquad (2)$$

where E_{heat} - energy loss e.g. as heat.

Such evaluation of energy was, however, insufficient during testing real apparatus in which after the time of usage operational wear appears e.g. a gasket or a transmitter. The better attitude towards would be more precise capturing of energy from transmitter to a hammer, because devices becoming older change their characteristic of work. It is suggested to analysis not only kinetic energy but phase portrait of pendulum after a shockwave generation. This diagram shows more information about dynamics of the work of device not only one value – the kinetic energy. Trajectory from the phase portrait for pendulum was defined as a relation ϱ state variables of dynamical system: the amplitude and the angular velocity:

$$\frac{d\theta(t)}{dt} \, \varrho \, \theta(t) \qquad (3)$$

Thanks to the usage quadrature encoder it was possible to detect the change of the pendulum motion sense and therefore to detect the maximum value of its amplitude. For the need of this research on the portraits the trajectories were trimmed up to this moment. In ideal situation i.e. for the simple pendulum phase portrait trimmed as assumed above would consist of trajectory in the shape of a quarter of ellipse, where semi-major axis is amplitude and semi-minor axis is the angular velocity.

AI Model

Data set for AI model was created from measurements conducted during experiments. Set required preparation which consisted of (Keras, sklearn libraries and TensorFlow were used):

1. Data was loaded from CSV files generated by encoder driver and software. Files contained in the following lines series of discrete value of time for the following values of pendulum amplitude.
2. On the basis of values from p.1 angular velocities were calculated.
3. Series were labelled as <letter><number> for 17 classes, where letter meant the type of transmitter (e.q. A - acupunctural, R - radial), number - treatment power (for radial transmitter 1..9, for acupunctural 2..9, power level 1 for acupunctural transmitter was too low to move pendulum)
4. All data were merged into one set.
5. Trajectories including wrong data and outliers (resulting from measurement error or imperfect measurement instrument) were rejected.
6. Labels were encoded.
7. Statistical feature extraction (2-nd and 4-th central moments) was done for neural network containing hidden Dense layer.

During AI model tuning cross-validation (5 folds) technique was used for the achievement of reliable work results for the model. Data set contained 1100 trajectories classified to 17 classes due to type of transmitter, power and its level of operational wear.

Results

Using the presented test bench and the method of measuring described before a series of experiments were conducted registering pendulum motion as a result of the shockwave generating. For each apparatus settings the experiment was repeated 60 times because the continuous medical procedure was used (1 Hz, a one minute measurement interval). Measured trajectories were averaged. In the diagrams the angular velocity was expressed by radians per seconds while the amplitude for decipherable was expressed by degrees.

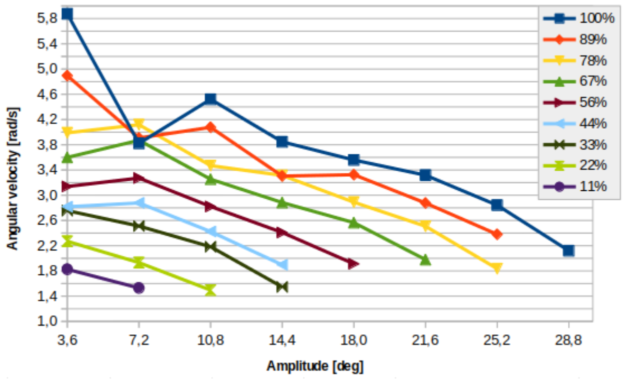

Fig 3. Trajectories for different powers of therapy

A phase portrait in Fig.3 presented trajectories for different powers of therapy using the electromagnetic applicator for the same type of the transmitter (a radial transmitter). Power of the electromagnetic apparatus (Rosetta CE V2.01, MCU V1.12) expressed in percentage corresponds to the solenoid voltage.

The shape of the trajectories from Fig.3 resembles mentioned a quarter of the ellipse. It also understandable that an increase in the device's power results in an increase in the trajectory length. In another words, it results in an increase in the pendulum amplitude. Reasonably evenly trajectories are far away from each other which means that an increase of the power of the apparatus results in an increase in a shockwave energy in a proportional manner. For two highest powers certain anomaly exists in the form of the local minimum in the second measurement. It requires further experiments and analysis.

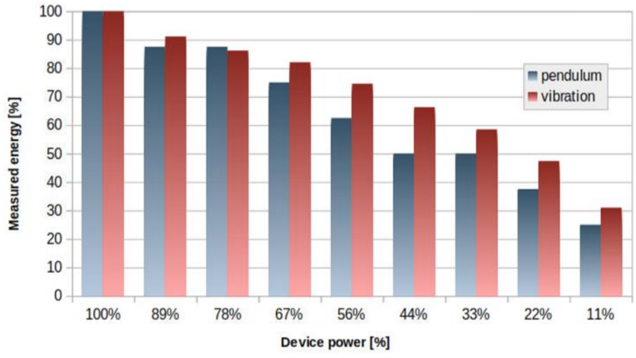

Fig 4. Comparison of the methods of the energy measurement

To verify whether presented the method of energy measurement is sensible, totally different experiments using the vibrometer, as shown by Sawicki et al (2022), were conducted. Measured signals were integrated using Newton-Cotes method and values were averaged. Such calculated values were compared with values that were measured using the pendulum. To make it possible to compare two different methods all values were rescaled to percentage values, i.e. each value was referred to the received value of the maximum power. In Fig.4 histogram comparing two methods of the shockwave energy measurement is shown. The value for pendulum method is lower than the value for vibrometer due to (2). The exception of the power 78% occurred because too low resolution of encoder was used (step for amplitude equalled 3,2 degree).

It seems that the suggested method may find usage in the diagnostic of the ESWT device. It might be the precise statistics analysis of these two methods.

Having registered phase portraits for the different types of transmitters and the different level operational wear it was possible to prepare AI agent supporting the work of the service point diagnosing and repairing these devices. Currently, this is done in this way that the apparatus being repaired is disassembled and its units are analysis to detect defects. It requires significant effort.

Benefiting from the experiments' results AI model was trained many times. 200 epochs as a hyperparameter were assumed. EarlyStopping technique, which was sensitive for the change of the value of loss metric on validation set, was used in order not to overfit the AI model. The model was tuned using data set for the choice of the neural network architecture and optimizer. As an activation function ReLU was used.

Training process was started from the long short-term memory neural network (RNN) as a solution advised by Wójcik et al (2023) for time series. It consisted of the hidden layers (using class names from Keras API presented in the book Chollet (2021)):

1. LSTM layer (64 units)
2. Dense layer (64 units)

Unfortunately, the average accuracy (taken from the cross-validation results) on test set was terribly low (at the random class selection level).

Thus, the model architecture was changed choosing convolution neural network (CNN) suited to series with various lengths (in this case trajectories). It consisted of hidden layers:

1. Convolution layer (64 filters)
2. Convolution layer (128 filters)
3. Convolution layer (128 filters)
4. Dense layer (64 units)

This time satisfactory values of accuracy were achieved (above 70%). However up to this moment AI model learnt directly whole trajectories. Therefore, in the third stage it was resigned to this approach. Statistical feature extraction was done and these features were treated as data set. The following architecture of AI model was suggested:

1. Dense layer (64 units)
2. Dense layer (64 units)

The satisfactory results were achieved again. The summary of these training processes can be found in Table 1. In the next experiments convolution solution was used.

Table 1. Comparison of AI architecture

AI architecture	The average accuracy on test set after cross-validation [%]
RNN	8,91
CNN	77,18
Dense	76,09

Having chosen AI architecture, it was tried to choose optimizer from, shown in the book by Chellot (2021) and paper by Mehmood et al (2023): Adam, SGD, RMSprop, NAdam, AdamX. In Fig.5 the comparison of optimizers in terms of accuracy on validation set. Due to EarlyStopping technique training processes were stopped at different epochs. Optimizers Adam, NAdam, RMSprop obtained almost similar scores. For the further experiments Adam was used.

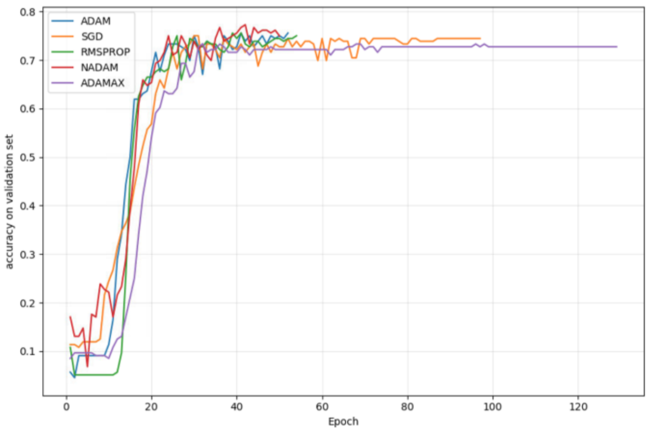

Fig 5. Comparison of optimizers

Other hyperparameters (like batch size) were not tuned. Typical values of these hyperparameters, which were suggested by manuals and samples, were used.

Conclusions

As it was mentioned in the abstract and the introduction of the following paper the research began with the usage AI agent to support the process of the anomaly detection of ESWT device work. Developing of AI agent should begin with preparation of the training set. Thus, the measurement instrument and the method were suggested. From the one side it lets the fast and the uncomplicated energy measurement and from the other side it provides so many samples and pieces of information to make it possible to teach AI. The second part of this paper was trial to design AI model letting to recognise the apparatus and their operational wear on the basis of the pendulum trajectories.

Long short-term memory architecture (LSTM) for which the hope was placed in did not work. It is suspected that various length of trajectories were responsible for it and therefore AI model did not learn the patterns of trajectories. The best in the terms of average accuracy on test set (for cross-validation, 5 folds) solution was neural network with convolution hidden layers. For this architecture Adam optimizer was chosen. Due to the fact that accuracy was below 100%, it was decided to analyse which apparatus mistaken with which. For this purpose average confusion matrix presented in Fig.6 as heatmap was used.

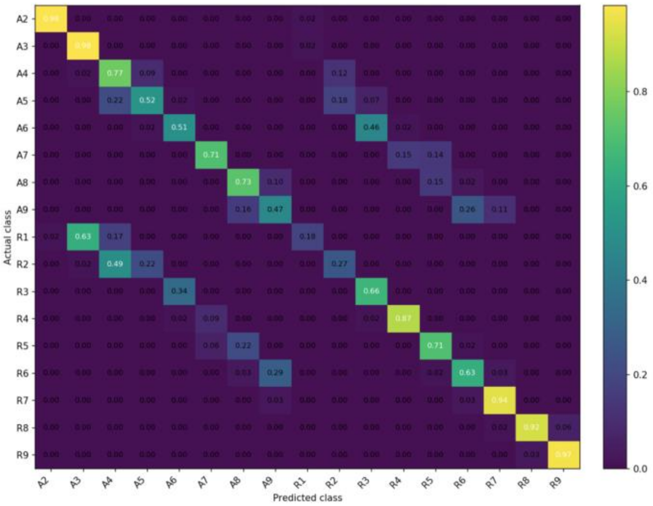

Fig 6. Confusion matrix

The diagonal on the heatmap (Fig.6) is noticeably light for the outer vertices which means that AI model recognised the transmitter the best for low and high power. Clearly noticeable are lighter parts on the heatmap symmetrical with respect to the diagonal. Model had tendency to confuse types of transmitters for close values of power. For example, trajectories were confused such as A6-R3, A8-R5, etc. In another words what is a trajectory for radial transmitter of the given power it is acupunctural transmitter for higher power. It results from pendulum mechanics movement, where its amplitude in this application depends only on shockwave energy. Whereby, due to mounting of applicator in measurement instrument, at different angles, it happens that bob may not hang on freely. Thus, it is important not only the height above which bob moves up, but also what is the acceleration of the bob in discrete points of its trajectory.

Future works

Above all before capturing a large set of portraits, which should serve to machine learning encoder resolution should be increased. For this purpose industrial inclinometer was order and it will substitute the current encoder.

Out of conducted researches it can be observed that AI model has a problem with differentiating specific power for the same transmitter or types of transmitter for the close power. The purpose of conducted researches is the possibility of recognising not the power or type of transmitter but its level of operational wear. Thus, it seems that one sample should not consist of one trajectory for the given power, but a sequence of trajectories for all possible powers. In another words AI model learns recognising transmitter on the basis of pendulum behaviour for all powers. Such attitude will be area for the further research.

References

- Mehmood, F., Ahmad, S. and Whangbo, TK. (2023) ‘An Efficient Optimization Technique for Training Deep Neural Networks,’ *Mathematics*
- Chollet, F. (2021) ‘Deep learning in Python,’ *Manning Publications*
- Sawicki, M. (2022) ‘Estimating the displacement of a shockwave therapy device's transmitter into the patient's tissue using the finite element method,’ Silesian University of Technology, diploma thesis
- Reinhardt, N., Dick, T., Lang, L., Radermacher K. and de la Fuente, M. (2021) ‘Hybrid Test Bench for High Repetition Rate Radial Shock Wave Measurement,*’ Curr. Dir. Biomed. Eng.*
- Reinhardt, N., Wegenaer, J. and de la Fuente, M. (2022) ‘Influence of the Pulse Repetition Rate on the Acoustic Output of Ballistic Pressure Wave Devices,’ *Sci. Rep.*
- Loske, A.M. (2017) ‘Medical and Biomedical Applications of Shock Waves; Shock Wave and High Pressure Phenomena,’ *Springer International Publishing*, Switzerland
- Császár, N.B.M., Angstman, N.B., Milz, S., Sprecher, C.M., Kobel, P., Farhat, M., Furia, J.P. and Schmitz, C. (2015) ‘Radial Shock Wave Devices Generate Cavitation,’ *PLoS ONE*
- Sawicki, M. and Maćkowski, M. ‘Station for recording the energy of a therapeutic shock wave and its shape in three-dimensional space in an aqueous medium,’ The Patent Office of the Republic of Poland, P.443369 (patent application).
- Milutinović, J., Hristov, N., Jerković, D., Markovic, S. and Živković, A. (2019) ‘The application of the ballistic pendulum for the bullets velocity measurements,’ *IOP Conference Series: Materials Science and Engineering*
- Sawicki, M., Maćkowski, M. and Płaczek, M. (2022) ‘The phenomenon of loss of energy flux density in pneumatic and electromagnetic generators for EPAT therapy,’ *Applied Sciences*, vol. 12
- Wójcik, D., Rymarczyk, T., Maciura, Ł., Oleszek, M. and Adamkiewicz, P. (2023) ‘Time Series Recognition with Convolutional and Recursive Neural Networks in BSPM,’ *International Interdisciplinary PhD Workshop (IIPhDW)*