

Novel Method for Detecting the Stage of Arthrosis and Femoroacetabular Impingement Using a Gyroscopic Sensor and Neural Networks

Nová metoda pro detekci stadia artrózy a femoroacetabulárního impingementu s využitím gyroskopického senzoru a neuronových sítí

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ABSTRACT

PURPOSE OF THE STUDY

Femoroacetabular impingement syndrome is a complex, often post-traumatically developing impairment of the hip joint, characterized by ambiguous symptomatology, which makes early diagnosis difficult, especially in the early stages.

Experimental retrospective study was carried out to evaluate the usability of a triaxial gyroscopic sensor in routine practice as an additional indication criterion for operative versus conservative treatment procedures.

MATERIAL AND METHODS

92 patients were included in the retrospective study, and 62 completed the investigation. All patients signed informed consent. A gyroscopic sensor was placed on the right side of the pelvis above the hip joint, and the patients walked approximately 15 steps. Furthermore, an evaluation of the data during stair climbing and a complete clinical examination of the dynamics and physiological movements in the joint was carried out.

Data measured with a gyroscopic sensor were processed using differential geometry methods and then evaluated using spectral analysis and neural networks. The proposed technique of diagnosing FAI using gyroscope measurement is a fast, easy-to-perform method.

RESULTS

Our approach in processing gyroscopic signals used to detect the stage of arthrosis and post-traumatically developing FAI could lead to more accurate early detection and capture in the early stages.

CONCLUSIONS

The obtained data are easily evaluated, interpretable and beneficial in diagnosing the early stages of FAI. The results of the conducted research showed this approach to more accurate early detection of arthrosis and post-traumatically developing FAI.

Key words: wearable sensors; osteoarthritis; mathematical biophysics; telemedicine.

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INTRODUCTION

Femoroacetabular impingement syndrome is a complex, often post-traumatically developing impairment of the hip joint: Pun, Kumar and Lane 2015 (14), Matsumoto, Ganz and Kanduja, 2020 (12), Glyn-Jones et al. 2015 (6), often characterized by ambiguous symptomatology, which makes early diagnosis difficult, especially in the early stages: Kuhns et al. 2015 (9, 10), Emary 2010 (4). The aim of this paper is to verify whether the values measured by the mobile wireless gy-

roscope correspond to the findings of the degree of post-traumatic degenerative joint damage during its clinical examination and to determine the possibilities and limitations of using the data obtained by measuring with a gyroscopic sensor for the early detection and diagnosis of FAI and to evaluate the usability of this data as an additional indication criterion when choosing an operative versus a conservative procedure.

There are several methods for establishing a diagnosis of FAI, including especially projectional radiography. Anterior-posterior pelvis and a lateral image of the

hip in question should be attained: Swagerty, Hellinger and Daniel 2001 (16). A 45-degree Dunn view is also recommended. Passive internal rotation of the hip during flexion should be assessed during physical exam because a range of motion is reduced.

The cornerstone of diagnosis is deciding whether FAI needs to be treated operatively, either by arthroscopic or open surgery: Kuhns, Frank and Pulido 2015 (9), Zhang et al., 2016 (17), Byrd et al. 2013 (2), or whether the patient will be treated conservatively, as for example in (Khan et al., 2015 (7). More details can be found in Khan et al. 2016 (8).

For these reasons, it would be advisable to have a simple diagnostic method available that could be used in daily practice, because in some cases FAI is only discovered late during routine X-ray examinations: Abellán et al. 2011 (1), Frank et al. 2015 (5). There were several additional methods proposed, for example in knee osteoarthritis analysis of vibroarthrographic signals was studied by Lee et al. 2012 (11).

Design

A retrospective experimental study was conducted at the trauma department of the Pardubice Region Hospital in the years 2015 to 2020. A total of 92 patients were included in the study, of which 62 completed the study. All patients signed informed consent. In terms of ethical approval, all procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. All participants gave written consent for anonymous data analysis. Since the research does not involve drug testing or invasive testing, there is no need for an ethics committee submission for this study.

To be included in the study, initial entry criteria were defined, and the history of hip joint injury history was monitored. Furthermore, a thorough clinical examination of the patient was carried out. The confirmed stage of osteoarthritis was determined based on X-ray imaging, ultrasonography, and magnetic resonance and the indication for arthroscopic surgery. Exclusion criteria were morbid obesity (body mass index greater than 35), inability to complete the walking test, and lack of completion of all clinical and paraclinical examinations during the study. There were 35 men and 27 women among the patients, the average age was 41 ± 12 years, and the average weight was 74 ± 13 kg. A total of 19 patients had stage 1 osteoarthritis, 31 patients had stage 2 osteoarthritis, and 12 patients had stage 3 osteoarthritis on the plain anteroposterior hip radiograph scale: Swagerty, Hellinger and Danie, 2001 (16).

A gyroscopic sensor was placed on the right side of the pelvis above the hip joint, and the patients walked approximately 15 steps.

MATERIAL AND METHODS

A wireless sensor was used for the measurement to eliminate any limitation of the patient's movement. We used the MBIENTLAB METAMOTION type, which consists of a Nordic Semiconductor wireless chip that transmits measured data via a 2.4 GHz Bluetooth network (MBientLab, 2022). The sensor consists of an accelerometer and a gyroscope. The sensor was placed on the right side of the pelvis above the hip joint and the patients walked approximately 15 steps. Furthermore, an evaluation of the data during stair climbing and a complete clinical examination of the dynamics and physiological movements in the joint were carried out. The three axes of the gyroscope signal were recorded as a time series with a sampling frequency of 200 Hz.

During the evaluation, these three signals were considered time series of projections of the measured phenomena into three orthogonal axes. Euclidean invariants of differential geometry, arc length, and Cartan curvature were then used as descriptors of human movement characteristics. Arc length is a mathematical object invariant to the $SO(3) \times \mathbb{R}^3$ group, so it is translation and rotation invariant in Euclidean space and thus independent of the exact sensor location. The arc length is calculated as follows:

$$s(t) = \int_0^t \sqrt{\sum_{i=1}^3 \left(\frac{dG_i(\tau)}{d\tau} \right)^2} d\tau,$$

where G_i is the i -th signal from the gyroscope, and τ is the sampling time. To eliminate the natural linear trend of the arc length, the derivative was used as input to the next part of the signal processing. The derivative $s(t)$ of arc length (DAL) was calculated as the difference between two adjacent samples at each sampling time. The arc length and Cartan curvature approach has already proven to be a powerful tool in biosignal processing: Studnička 2011 (15), Cimr et al. 2021 (3).

Based on these differential geometry invariants, time series representing locomotion were calculated for each patient. The derivative of the Euclidean arc length and the first Cartan curvature were calculated for processing. These characteristic curves were then assigned to individual patients, and processing was carried out on other types of examinations to determine whether the method could provide information on other pathologies. In further processing, neural networks were used as a modern tool for time series analysis. The basis for the neural networks was either the classified time series themselves, but also experiments with image recognition, where the input was the continuous wavelet transformation (CWT), which is a method used to analyze the contained frequencies with extremely sensitive resolution.

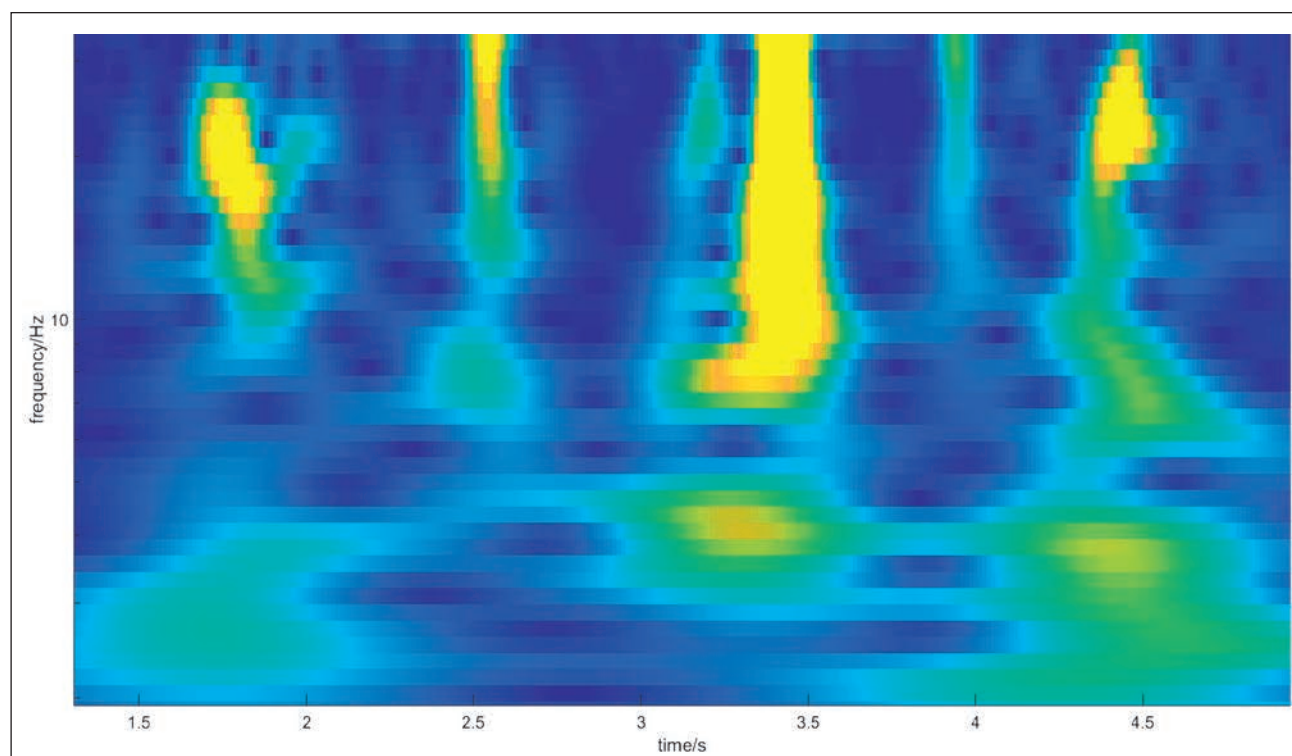


Fig. 1. Example of a five-step CWT magnitude scalogram of a patient with stage 2 osteoarthritis. Magnitude is represented by color, where blue indicates the low magnitude and yellow is high. The blue clusters (spectra minima) are related to crepitus-induced resonances.

The first was an experiment with the differentiation of the stage of osteoarthritis (3 categories), where the input was just individual CWT walking records (Fig. 1).

The Matlab environment was used to test the neural network, enabling high settings variability. The images were divided into three classes according to the stage of osteoarthritis. The images were loaded as intensity matrices, from which intensity vectors were created, i.e., each image was represented by one vector. The „Pattern recognition and classification“ option was chosen as the neural network type. Due to the input data size, 30 hidden neurons were used. The network architecture is shown in Fig. 2.

The data were distributed randomly; the training was carried out using the „Scaled Conjugate Gradient“ function: Möller 1993 (13). The training function updates the neuron weights using the scaled conjugate

gradient method. It can train any network if its transfer functions have a derivative. During these tests, it was found that the neural network had problems distinguishing stages 2 and 3, therefore, for subsequent processing, stages 2 and 3 were combined in a separate category, and the learning of the neural network took place only in two classes, i.e., stage 1 and stage 2+3. An average accuracy of 88%, a sensitivity of 85%, and a specificity of 81% were achieved. This proved that neural network processing is a suitable way to process image data of CWT spectra.

The parameters obtained from the measured time series were compared for further analysis. Specifically, we examined the integral value over selected frequencies in the Welch spectrum of the delinearised arc length calculated from the data measured by the gyroscope with other patient characteristics. For these purposes,

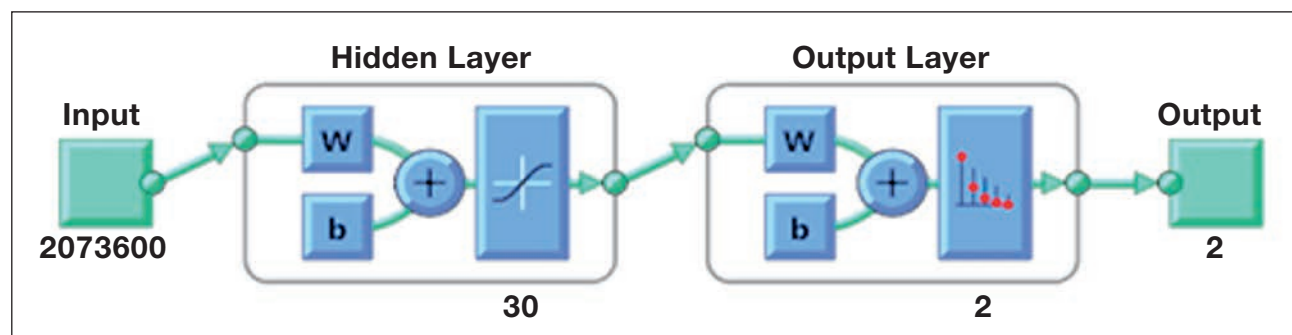


Fig. 2. Neural network architecture in the Matlab environment.

Table 1. Representation of lesion types depending on the degree of osteoarthritis

Stage I				Stage II				Stage III			
19				31				12			
CAM		PINCER		CAM		PINCER		CAM		PINCER	
Finding	Verified	Finding	Verified	Finding	Verified	Finding	Verified	Finding	Verified	Finding	Verified
8	7	11	9	22	8	9	8	6	6	6	5

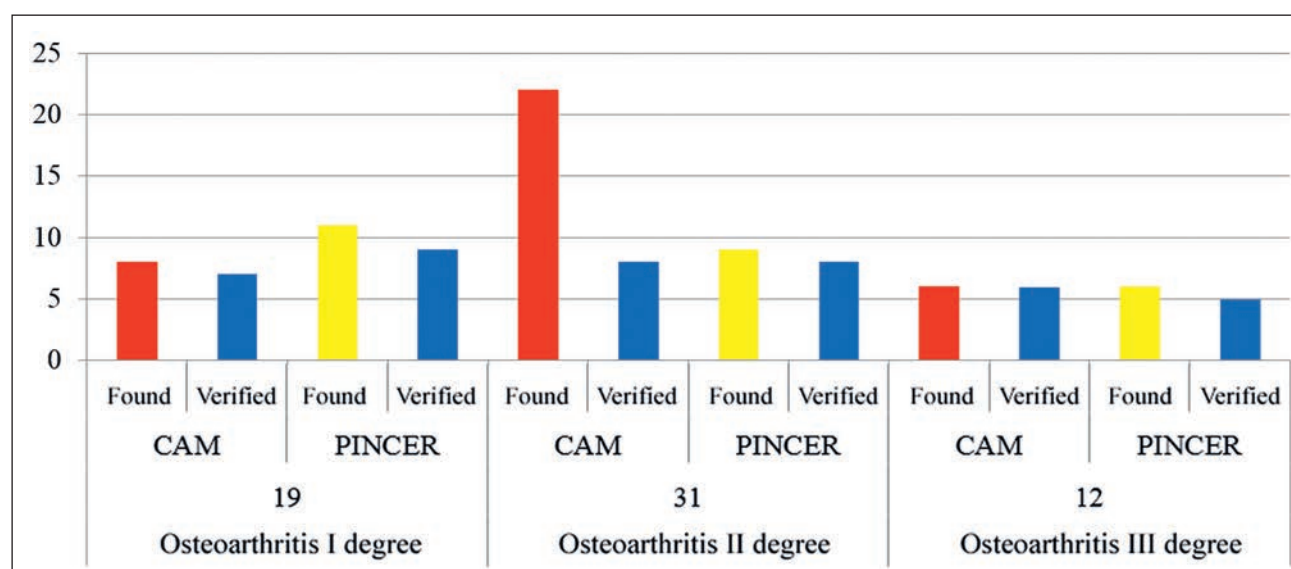


Fig 3. Frequency of lesions depending on the degree of osteoarthritis.

we always selected a given characteristic. We tried to find the most suitable part of the frequency spectrum for it, which showed the maximum correlation with these characteristics. Considering that measurement using a gyroscope can be regarded as an alternative to a test for a given parameter, we chose appropriate statistical variables that indicate the strength of the test, sensitivity, specificity, and positive predictive value of the given test. Sensitivity expresses the success with which the test captures the presence of the monitored condition (disease) in a given subject. Specificity represents the ability of the test to accurately select cases in which the examined sign (disease) occurs. A positive predictive value can be characterized as a correct assumption, i.e., the probability that a person is ill when the test has a positive response. The aim was to determine the statistical parameters of the CAM or PINCER lesion detection test in individual patients based on their results in paraclinical examinations.

RESULTS

We compared the obtained data with the results of other paraclinical examinations. In grade I osteoarthritis, we found CAM lesions in 8 patients out of a total of 19 monitored, 7 of them were verified by the described gyroscope data analysis. The PINCER lesion was de-

tected in 11 patients, 9 of them were confirmed. In the case of osteoarthritis II. degree, out of the total number of 31 CAM lesions were identified in 22, of which 18 were verified. PINCER lesions appeared in 9 and in the case of 8 patients, this finding was verified. With osteoarthritis III. degree, 12 patients were followed, 6 with CAM lesions, and all 6 cases were confirmed. In the case of the PINCER lesion, the finding was manifested in 6 patients and 5 of them were verified (see Table 1 and Fig. 3).

The following table shows the evaluation of selected statistical variables concerning the number of found and verified types of lesions in relation to the degree of osteoarthritis (Table 2).

15 probands completed the dynamic walking test for 15 steps within 10 seconds, 26 patients completed this test within 10 to 15 seconds. 18 patients needed 16 to 25 seconds to complete this test, and 3 patients achieved more than 25 seconds. The frequency of probands in individual time intervals is captured in the Fig. 4.

Another phenomenon investigated was passive joint motion when the sensor was loaded above the greater trochanter. 22 patients accomplished full flexion. A CAM lesion was found in 17 of them, of which the gyroscope verified 14 cases. The PINCER lesion was shown in 5 patients, 3 patients were subsequently confirmed. Reduced flexion by 15° was seen in 22 patients,

of which CAM lesions were detected in 10 and verified in 9 cases. Pincer lesion out of 11 found was verified in 7 cases. Another significant reduction in flexion, in the value of 30°, was recorded in 18 respondents. Out of 10 diagnosed CAM lesions, 4 were verified, in the case of Pincer lesions, 3 out of 8 cases were verified.

Table 4 shows that with full flexion, the positive predictive value of the test is relatively high. In the case of sensitivity, i.e., the success of detecting the presence of the disease, the highest value is in patients in which the flexion is reduced by 15°.

The next part of the test was related to the abduction. The range of this movement was recorded in 25 patients. 6 out of 10 patients with CAM lesions were verified, and 7 out of 15 patients were subsequently verified in the case of Pincer lesions. Reduction of the

Table 2. Percentage expression of monitored values for frequency of osteoarthritis types

Degree of osteoarthritis	Sensitivity	Specificity	Positive predictive value (PPV)
Grade I	88 %	82 %	78 %
Grade II	82 %	89 %	95 %
Grade III	100 %	83 %	86 %

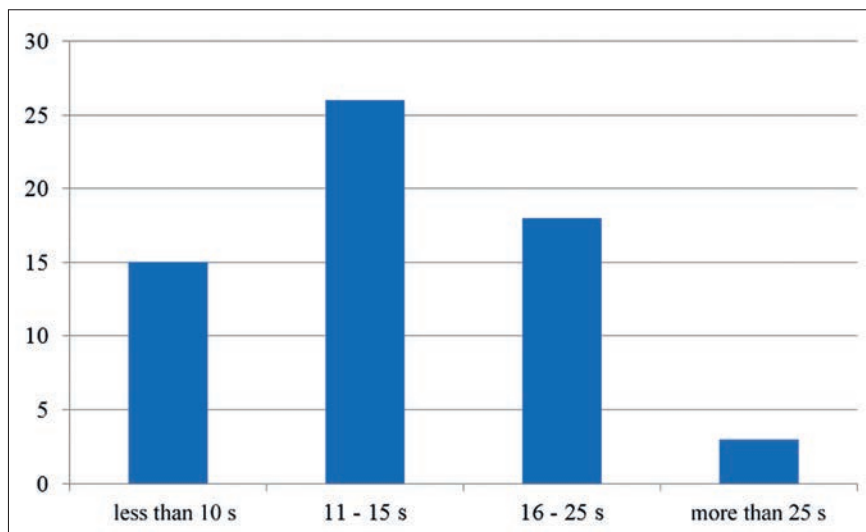


Fig. 4. Evaluation of the dynamic walking test.

Table 3. Frequency of patients according to flexion level and type of lesion

Range of flexion	CAM lesion		Pincer lesion	
	Finding	Verified	Finding	Verified
Full flexion	17	13	5	3
Decrease of 15°	11	9	11	7
Decrease of 30°	10	4	8	3

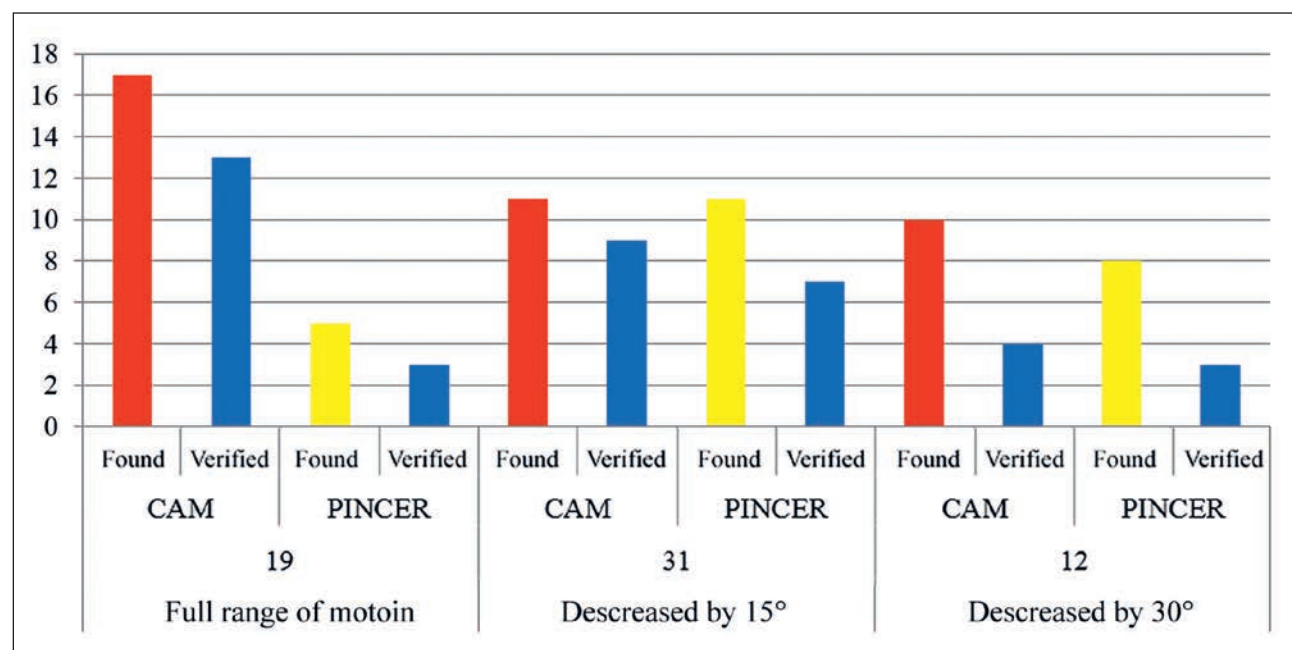


Fig. 5. Evaluation of flexion in connection with the type of lesion.

range to 10° concerned 28 patients. Of this number, 12 patients were diagnosed with a CAM lesion, confirmed with a gyroscope in 7 cases. Of the 16 diagnosed Pincer lesions, 9 cases were verified. Range reduction of more than 10° was detected in 9 patients, of which 4 were diagnosed with a CAM lesion, which was verified for 2 cases. For the Pincer lesion, which was found in 5 patients, 3 cases were subsequently confirmed by the gyroscope.

Table 4. Percentage expression of observed values at different flexion

Range of flexion	Sensitivity	Specificity	Positive predictive value (PPV)
Full flexion	75 %	50 %	86 %
Decrease of 15°	80 %	60 %	67 %
Decrease of 30°	57 %	50 %	57 %

DISCUSSION

X-ray, CT, and magnetic resonance examinations are used to diagnose FAI. The gyroscope can be regarded as an alternative, valid diagnostic method. As proven in repeated measurements, the three-axis gyroscope used by us is validly and positively capable of detecting and reliably repeatedly registering even asymptomatic patients in the initial stages of osteoarthritis and FAI. The examination was standardized with the possibility of simple repetition without any secondary burden for the patient. With a higher degree of osteoarthritis, the positive specificity of the captured values of the frequency curves in the monitored probands also increased. With the correct input in/out criterion division of patients, this method is simple, non-invasive, readily available, well and quickly implemented and evaluated, without special software support requirements. The initial investment is minimal, in the range of thousands of crowns per sensor. The examination can be repeated routinely and standardly without any problem and can be immediately evaluated directly, for example, in the mobile phone application. It also followed from our experience and measured data that the device could be one of the additional criteria for the correct and timely diagnosis of patients with FAI, a possible auxiliary indication guide for surgical performance, but understandably not the only one.

In patients diagnosed with FAI (X-ray image or MRI) who completed the experimental study, it was possible to reliably and positively demonstrate the detection of changes in movement frequency curves in the affected joint. However, it was impossible to identify a clinical correlation between the individual types of FAI disability (CAN, Pincer, mixed type) from the measured data. This can probably be attributed to the type and capacity options of the sensor, which captures signals from the hip joint across the board, so far without the possibility of a targeted focus on specific anatomical conditions and degenerative changes in the hip.

From the collected data, a higher percentage correlation of the results measured by the gyroscope compared to the diagnosis of X-ray for higher degrees of osteoarthritis, where the sensitivity and positive predictive value increased. This trend was further observed in assessing complex rotational movements and the walking test. It can probably be attributed to longer and more pronounced exposure to the conflicting position and movement of degeneratively changed structures inside the joint. When analyzing the data of the questionnaire assessment of the pain perceived by the patient, the accentuation of the increase in sensitivity and specificity at the lower levels of the pain scale is worth noting. This fact again corresponds to the possible early detection of asymptomatic patients diagnosed with FAI.

All patients included in the study were indicated within the standardized criteria of the indication seminar for an arthroscopic procedure on the hip joint for diagnosed and symptomatic FAI. Here, on a medium-sized sample of patients as part of an experimental study, it was possible to positively demonstrate the correspondence between individual paraclinical methods and the measured data values. It was possible to safely and positively identify an increase in the specificity and sensitivity of detection for particular types of degenerative hip disease, respectively, between the distribution of types of FAI (CAM / Pincer) on individual mathematical models. Considering the possibilities of the sensor, the question of developing its further use for diagnosing pathologies on other large joints is raised.

CONCLUSIONS

Nowadays, the issue of FAI is coming to the forefront of interest, not only among the professional public. Due to its diversity in clinical manifestations, the often gradual, intermittent onset of symptoms, often at first glance very disparate, it is probably sometimes neglected. In these circumstances, a relatively large number of patients are still not correctly diagnosed in time and, therefore, not indicated for appropriate treatment. Early recognition, correct diagnosis, and therapy indication are crucial for patients with developing FAI. Early detection of the disease can prevent, or at least suspend, the acceleration of the development of higher stages of osteoarthritis and degenerative changes in the joint.

We found the described method a well-usable tool for monitoring the progress of arthrosis and the development of the early stages of FAI, using technically simple clinical examinations of patients and data from gyroscopic sensors. The experimentally investigated method of diagnosing FAI using triaxial gyroscope measurement is fast and easy to perform without burdening the patient. The obtained data are quickly evaluated, interpretable and beneficial in diagnosing the early stages of FAI. The results of the conducted research showed that new approaches in the processing of gyroscopic signals used to detect the stage of arthrosis and

post-traumatically developing FAI could lead to its more accurate early detection and capture in the early stages.

The statistics of the evaluated data obtained in the study showed a significantly significant correspondence with the diagnosed degree of arthrosis in patients with a post-traumatically affected hip joint. The evaluated signal spectra for individual degrees of arthrosis agreed with the X-ray image and magnetic resonance findings and complemented the patient's clinical examination.

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