MMSL Military Medical Science Letters Since 1925

Mil. Med. Sci. Lett. (Voj. Zdrav. Listy) 2024, 93(4), 323-334
ISSN 2571-113X (Online)
DOI: 10.31482/mmsl.2023.038

ORIGINAL ARTICLE

A SYSTEM FOR WIRELESS MEASUREMENT OF HUMAN BIOMECHANICS

Pavel Holeka [1], Filip Studnička [2], Jan Štěpán [2], Jan Matyska [3], Jan Šlégr [2], Šárka Odložilová [1], Ján Zajak [1], Jiří Páral [1] ✉

[1] Department of Military Surgery, Military Faculty of Medicine, University of Defense, Hradec Králové, Czech Republic
[2] Department of Physics, Faculty of Science, University of Hradec Králové, Hradec Králové, Czech Republic
[3] Center for Advanced Technologies, Faculty of Science, University of Hradec Králové, Hradec Králové, Czech Republic

Received 8th October 2023.
Accepted 18th October 2023.
Published 2nd December 2024.

Summary

Background

Femoroacetabular impingement syndrome (FAI) is a complex, often post-traumatically developing impairment of the hip joint. It is characterized by ambiguous symptomatology, which makes early diagnosis difficult.

Aim

The study was conducted to evaluate the applicability of a triaxial gyroscopic sensor in routine practice as an additional indication criterion for operative versus conservative treatment procedures.

Methods

Ninety-two patients were included in the experimental retrospective study and 62 completed the examination. All patients signed informed consent. A gyroscopic sensor was placed on the right side of the pelvis above the hip joint and patients walked approximately 15 steps. Data were also evaluated while the patients climbed stairs. A complete clinical examination of the dynamics and physiological movements in the joint was performed. The data measured by the gyroscopic sensor were processed using differential geometry methods and subsequently evaluated using spectral analysis and neural networks.

Results

FAI diagnosis using gyroscopic measurement is fast and easy to implement. Our approach to processing the gyroscopic signals used to detect the stage of osteoarthritis and post-traumatic FAI could lead to more accurate detection and capture early in FAI development.

Conclusions

The obtained data are easily evaluated, interpretable, and beneficial in the diagnosis of the early stages of FAI. The results of the study show that this approach can lead to more accurate and early detection of osteoarthritis and post-traumatic FAI.

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

✉ University of Defense, Military Faculty of Medicine, Department of Military Surgery, Trebesska 1575, 500 01 Hradec Králové, Czech Republic
💻 jiri.paral@seznam.cz jiri.paral@unob.cz
☎ +420 737418490

Introduction

Femoroacetabular impingement syndrome is a complex, often post-traumatically developing involvement of the hip joint (1, 2). It is often characterized by ambiguous symptomatology, which makes early diagnosis difficult, especially in the early stages (3, 4). The first aim of this study was to verify whether the values measured by a mobile wireless gyroscope correspond to the clinical findings of the degree of post-traumatic degenerative damage of the joint. The second was to determine the possibilities and limitations of using gyroscopic sensor measurements for the early detection and diagnosis of FAI and to evaluate the applicability of these data as another indication criterion when choosing an operative versus a conservative procedure.

There are several methods for diagnosing FAI, such as projection radiography, where the aim should be to obtain an anteroposterior image of the pelvis and a lateral image of the relevant hip (5). In some cases an MRI examination is used (6), and Lee et al. investigated knee osteoarthritis by analyzing vibroarthrographic signals (13). A 45° Dunn's view is also recommended. Passive internal rotation of the hip during flexion should be assessed during physical examination because range of motion is reduced.

The basic goal of diagnosis is to decide whether it is necessary to treat FAI operatively, either by arthroscopic (6) or open surgery (4, 7, 8), or conservatively (9). More details can be found in the review by Ayeni *et al*. (10). For these reasons, it would be advisable to have a simple diagnostic method available in daily practice, because in some cases FAI is detected too late, during routine X-ray examinations (11, 12).

Method

A retrospective experimental study was conducted in the regional hospitals in Pardubice and Chrudim, Czech Republic, between the years 2015 and 2020. A total of 92 patients were included in the study, of which 62 completed the study. All patients signed informed consent. Regarding 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 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 did not involve drug testing or invasive testing, there was no need to submit proposals to an ethics committee for this study.

Entry criteria were defined for inclusion in the study, a history of hip joint injury was monitored, and a thorough clinical examination of the patient was performed. The confirmed stage of osteoarthritis was determined on the basis of X-ray imaging, ultrasonography, magnetic resonance, and the indication for arthroscopic surgery. Exclusion criteria were morbid obesity (body mass index [BMI] greater than 35), inability to complete the walking test, and failure to complete 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 plain anteroposterior hip radiographs (5).

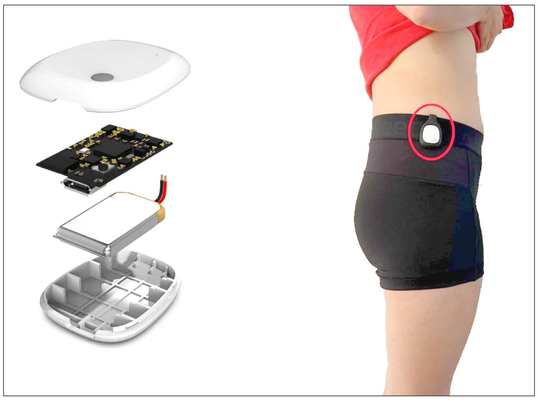

Figure 1. MBIENTLAB MetaMotion device, actual size 27×27×4 mm (left), location on the body (right).

A gyroscopic sensor was placed on the right side of the pelvis above the hip joint (see Figure 1) and patients walked approximately 15 steps (additional experiments showed that a short walk of 15 steps was sufficient to obtain sufficient data for analysis).

A wireless sensor was used for the measurement to eliminate any restriction of the patient's movement. We used the MBIENTLAB MetaMotion type, which consists of a Nordic Semiconductor wireless chip that transmits the measured data via a 2.4-GHz Bluetooth network (Figure 1). The sensor consists of an accelerometer and a gyroscope. It is wireless and can be placed in a charging station when not in use. The sensor was placed on the right side of the pelvis above the hip joint and the patients walked approximately 15 steps with standard walking. Placing the sensor directly on the patient during examination is quite easy. The sensor is placed about 4 cm cranially above the crista iliac, with the front side of the sensor pointing laterally. The sensor is fixed with either double-sided adhesive tape or with the holder supplied with the product (Figure 1). As we will see, the exact position of the sensor is not critical. Using the methods of differential curve geometry, the measured signal is projected as a multidimensional curve onto the given axes, and the parameters of this multidimensional curve, which are invariant to the resulting projection, are evaluated.

In addition, an evaluation of the data while walking up the stairs and a complete clinical examination of the dynamics and physiological movements in the joint were performed.

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 represented as time series of projections of the measured phenomena into three orthogonal axes. The 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 group SO (3)×$\mathbb{R}$3, so it is translationally and rotationally invariant in Euclidean space and thus independent of the exact location of the sensor.

Arc length was calculated as follows:

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

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 *s(t)* was used as input for the next part of the signal processing. The derivative of arc length (DAL) was calculated as the difference between two adjacent samples at each sampling time. The use of arc length and Cartan curvature to study time series has already proven to be a useful tool in biosignal processing (14, 15).

Based on these differential geometry invariants, time series representing their locomotion were calculated for each patient. For processing, the derivative of the Euclidean arc length and the first Cartan curvature were calculated. These characteristic curves were then assigned to individual patients for comparison with the results of other clinical examinations to verify whether the method could provide information on other pathologies. Specifically, the integral value over selected frequencies in the Welch spectrum of the delinearized arc length calculated from gyroscope data with other patient characteristics was investigated. A given characteristic was always selected for these purposes. We searched for the most suitable part of the frequency spectrum, which means it showed the maximum correlation with these characteristics. Considering that gyroscope measurement can be considered an alternative to a statistical test for a given parameter, we chose appropriate statistical variables that indicate the power, sensitivity, specificity, and positive predictive value of the given test. Sensitivity expresses the success with which the test captures the presence of the observed condition (disease) in a given subject. Specificity represents the ability of the test to accurately select cases in which the investigated condition (disease) occurs. A positive predictive value can be characterized as a correct assumption—that is, 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.

Table 1. Frequency of patients according to level of abduction and type of lesion.

Abduction range	Cam lesions		Pincer lesions	
	Finding	Verified	Finding	Verified
Full abduction	10	6	15	7
Reduction to 10°	12	7	16	9
Decrease above 10°	4	2	5	3

Table 2. Percentage expression of observed values during different abductions.

Abduction range	Sensitivity	Specificity	Positive predictive value
Full abduction	60%	47%	43%
Reduction of range to 10°	58%	56%	50%
Reduction of range above 10°	50%	60%	50%

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

Range of adduction	Cam lesions		Pincer lesions	
	Finding	Verified	Finding	Verified
Full abduction	19	14	24	20
Reduction to 10°	9	6	10	7

Table 4. Percentage expression of monitored values with different adduction.

Range of adduction	Sensitivity	Specificity	Positive predictive value
Full abduction	74%	83%	78%
Reduction of range to 10°	67%	70%	67%

Table 5. Frequency of patients by level of rotation and type of lesion.

Range of rotation	Cam lesions		Pincer lesions	
	Finding	Verified	Finding	Verified
Full internal rotation	23	18	10	7
Full external rotation	15	11	13	7
Decrease by 5°	11	7	11	8
Decrease by 10°	4	3	4	2
Reduction of more than 10°	1	1	3	2

Table 6. Percentage expression of monitored values at different rotations.

Range of rotation	Sensitivity	Specificity	Positive predictive value
Full internal rotation	78%	70%	86%
Full external rotation	73%	54%	65%
Range reduction by 5°	64%	73%	70%
Reduction of range by 10°	75%	50%	60%
Reduction of range by more than 10°	100%	67%	50%

Table 7. Frequency of patients according to BMI class.

BMI class	Cam lesions		Pincer lesions	
	Finding	Verified	Finding	Verified
I	26	22	12	11
II	10	7	9	9
III	2	1	3	1

Table 8. Percentage expression of monitored values for individual BMI levels.

BMI class	Sensitivity	Specificity	Positive predictive value
I	85%	92%	96%
II	70%	100%	100%
III	50%	33%	33%

Table 9. Frequency of patients according to the nature of the pain.

Degree of pain	Cam lesions		Pincer lesions	
	Finding	Verified	Finding	Verified
Without pain	5	2	5	3
Slight pain	7	5	8	5
Discomfort	13	12	10	9
Intermediate level	4	2	3	2
Significant pain	3	2	3	2
Unbearable pain	1	1	0	0

Table 10. Percentage expression of monitored values for individual degrees of pain.

Degree of pain	Sensitivity	Specificity	Positive predictive value
Without pain	40%	60%	50%
Slight pain	71%	63%	63%
Discomfort	80%	75%	80%
Intermediate level	50%	67%	67%
Significant pain	67%	67%	67%
Unbearable pain	100%	ON	100%

Table 11. Frequency of patients according to level of lameness.

Level of lameness	Cam lesions		Pincer lesions	
	Finding	Verified	Finding	Verified
Not lame	14	8	15	7
Slight limp	10	6	11	7
Moderate lameness	7	4	5	3
Failure to complete the test	0	0	0	0

Table 12. Percentage expression of monitored values for individual degrees of lameness.

Degree of lameness	Sensitivity	Specificity	Positive predictive value
Not lame	57%	47%	50%
Slight limp	60%	64%	60%
Moderate lameness	57%	60%	67%
Failure to complete the test	0%	0%	0%

Table 13. Frequency of patients according to the stair-climbing test.

Stair-climbing test	Cam lesions		Pincer lesions	
	Finding	Verified	Finding	Verified
Normal stair climbing	19	14	13	9
Needing a little help	10	7	11	8
Needing more help	4	3	5	4
Inability to complete	0	0	0	0

Table 14. Percentage expression of observed values during the stair-climbing test.

Stair-climbing test	Sensitivity	Specificity	Positive predictive value
Normal stair climbing	74%	69%	78%
Needing a little help	70%	73%	70%
Needing more help	75%	80%	75%

Results

The following section describes the results of selected clinical and paraclinical evaluated characteristics that have not yet been published and their comparison with the outputs of processing data from the gyroscope.

Abduction

The full range of this movement was recorded in 25 patients. Six out of 10 patients with cam lesions were verified, and in the case of pincer lesions, 7 out of 15 patients were subsequently verified. Reduction of the range to 10° was detected in 28 patients. Of this number, 12 were diagnosed with a cam lesion, which was verified 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 gyroscope.

When evaluating this type of bending, the success rate of capturing the presence of the disease is highest in the case of full abduction or an insignificant reduction in range. In cases where the reduction in the range of motion is greater than 10°, the highest specificity of the test is manifested.

Another variant of the evaluated movement was hip adduction. Forty-three patients managed this movement in full range. A cam lesion was found in 19, with subsequent verification in 14 cases. Of the 24 diagnosed pincer lesions, 20 cases were verified with the gyroscope. Adduction reduced by less than 10° was noted in 19 patients. Of the 9 cam lesions, 6 were verified, and for the pincer type, which was diagnosed in 10 cases, 7 were verified.

The observed statistical quantities reached higher values in the case of full adduction, but even when the extent of adduction was reduced the evidence of the test in all monitored quantities is relatively high.

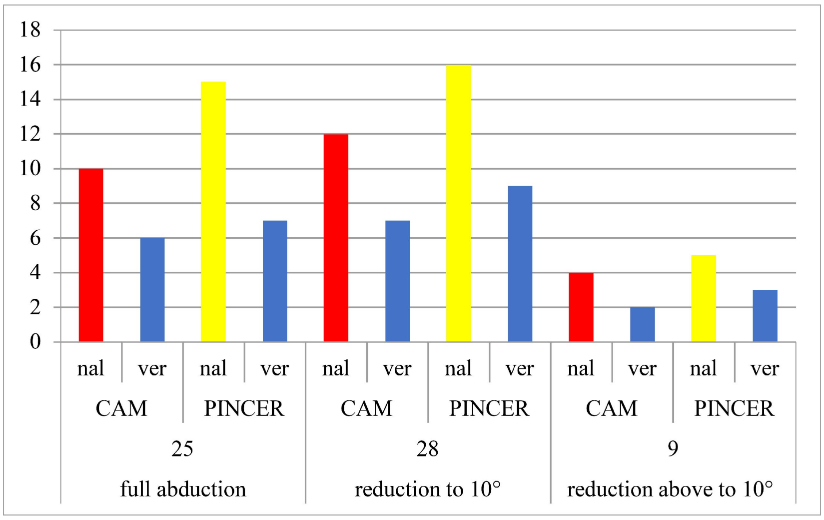

Figure 2. Evaluation of the level of abduction in relation to the type of lesion.

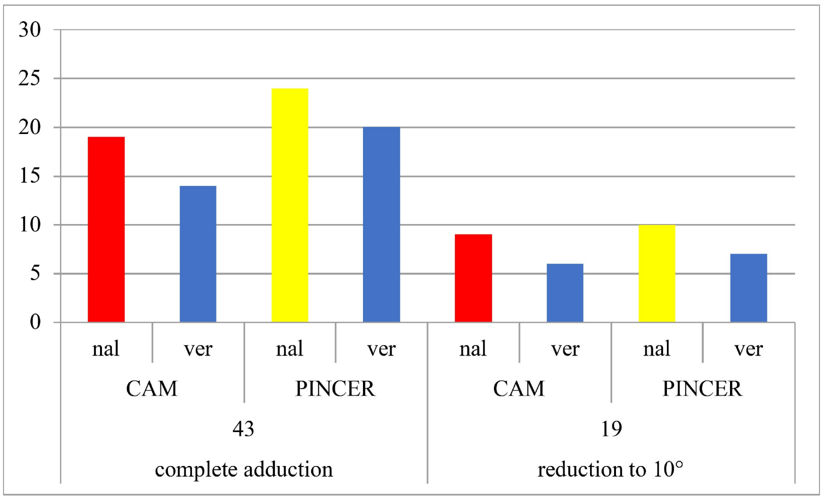

Figure 3. Evaluation of the level of adduction depending on the type of lesion.

Rotation

To assess rotational movement, internal and external rotation were monitored. Thirty-three patients achieved full internal rotation. Out of 23 diagnosed cam lesions, 18 patients were verified. Pincer lesions were diagnosed for 10 cases, of which 7 cases were verified by gyroscope. Twenty-eight patients performed a full terrestrial rotation: 15 patients had a cam lesion, and subsequently 11 of them were verified. Of the 13 pincer lesions found, 7 cases were confirmed. A decrease in rotation by 5° was detected in 22 patients, 7 of the 11 patients with cam lesions were verified. A pincer lesion was found for this range of motion in 11 patients and 8 were subsequently verified. A reduction of 10° was observed in 8 patients, of whom 4 had a cam lesion, of which 3 were verified. A pincer lesion was found in 4 patients but verified in only 2. A reduction greater than 10° was detected in 4 patients, including one with a diagnosed cam lesion, subsequently also verified. Of the 3 pincer findings, 2 were verified.

The highest values for prediction were achieved when full internal rotation was performed; in the case of external rotation it was not possible to trace a clear continuity. The sensitivity (i.e., the success rate of detecting the disease) was 100% in patients with a significant reduction in the range of external rotation.

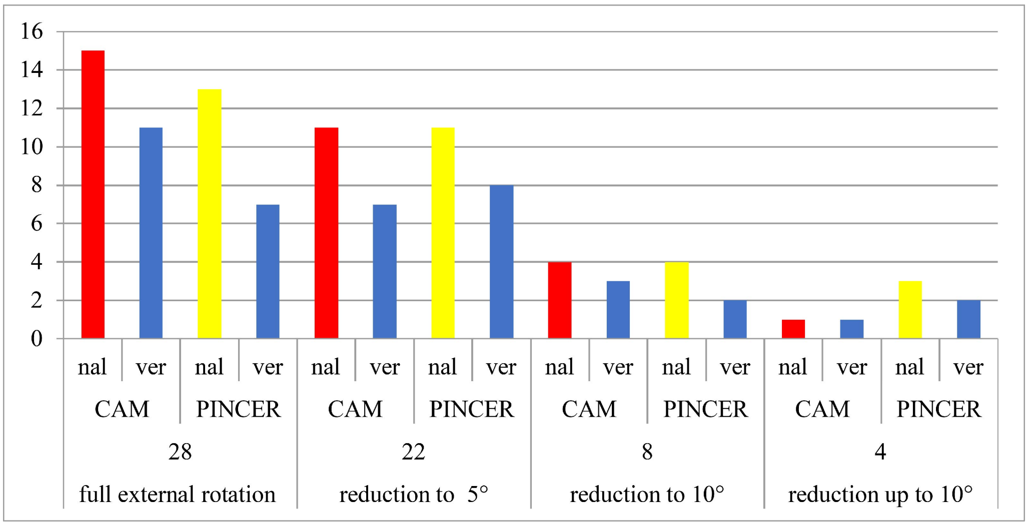

Figure 4. Evaluation of the level of external rotation depending on the type of lesion.

BMI

One of the evaluated criteria was the BMI, which was monitored according to the recommended criteria and classification. There were no underweight patients in the selected sample. Thirty-eight monitored patients had normal BMI (18,5 – 24,9). Of these, 26 were diagnosed with a cam lesion, and 22 of these lesions were subsequently verified. A pincer lesion was diagnosed in 12, and of these, 11 were verified. Nineteen patients fell into the overweight class (BMI 25–29,9), and of the 10 diagnosed cases with cam lesions, 7 were verified. Pincer lesions were found in 9 patients, and all were confirmed by gyroscope. Five patients were in BMI class III, obesity (BMI 30–34,9): 2 of them had a cam lesion, and one case was confirmed. The other 3 had diagnosed pincer lesions, and one of them was verified.

For patients in the first and second BMI classes, the selected statistical variables show high values; the use of the selected testing with the use of the gyroscope provided particularly reliable results. For patients with obesity, all the values of the statistical variables are low because the gyroscope was not able to conclusively evaluate the obtained signals.

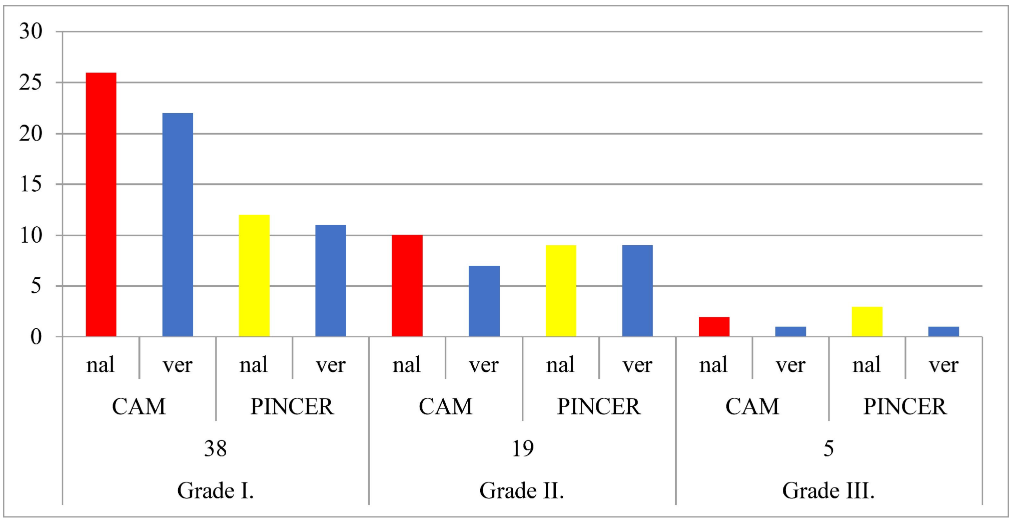

Figure 5. Expression of the frequency of patients according to the degree of BMI.

Pain

Another evaluated criterion was pain, which was evaluated using a 6-point scale. The first grade represented the absence of pain, which was reported by 10 patients. There were 5 patients with cam lesions, of which 2 were verified. Five cases were diagnosed with a pincer lesion, and 3 of them were confirmed by gyroscope. The second degree was slight pain, reported by 15 respondents; in 5 of them a cam lesion was found, and all 5 were verified. The pincer type was found in 8 cases with subsequent verification in 5. The third, mild degree of pain, was identified in 23 patients. Thirteen were found to have a cam lesion, of which 12 were verified, and 10 had a pincer lesion, of which 9 were verified. A moderate degree of pain was reported by 7 interviewees: 4 of them had a cam lesion, which was verified in 2 patients, and 3 had a pincer lesion, which was verified in 2. The fifth degree, significant pain, was reported by 6 interviewees including 3 patients with a cam lesion, of which 2 were verified by gyroscope, and one with a pincer lesion. Unbearable pain was reported by one patient with a cam lesion, which was confirmed by the gyroscope.

In evaluating the stated pain criterion, the gyroscope method was relatively highly efficient even in cases where patients reported minor or only mild pain.

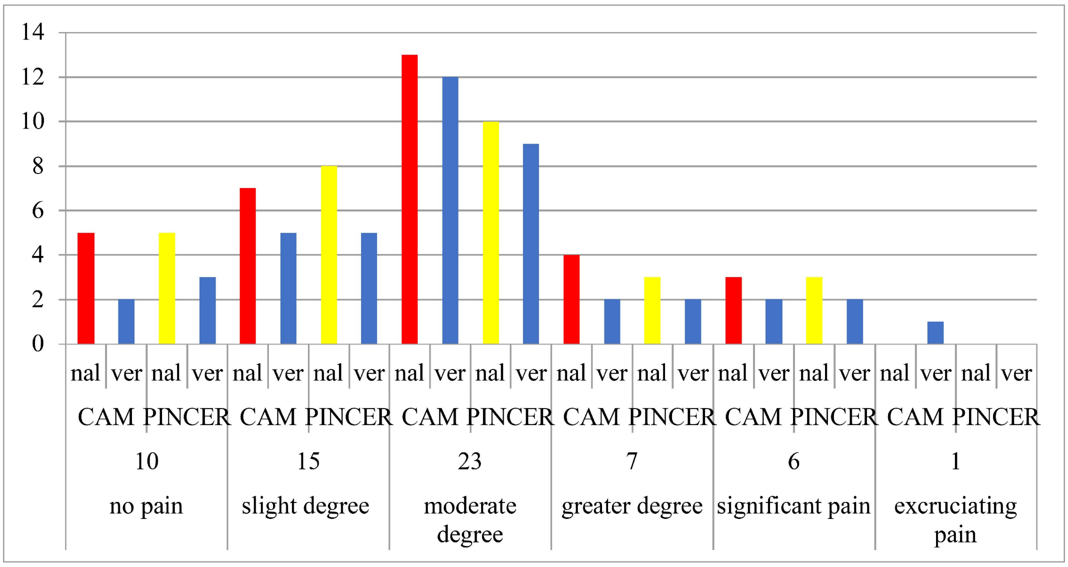

Figure 6. Expression of the number of patients according to the degree of pain felt.

Locomotion

Another criterion tested in patients was lameness, which was evaluated on four levels. The first was absence of lameness, which was met by 29 patients. Of these, 14 patients were diagnosed with a cam lesion, of which 8 were verified with the gyroscope, and 15 had a pincer lesion, of which 7 were verified. The second level was mild symptoms of lameness, which were manifested in 21 patients. A cam lesion was found at this level in 10 cases and verified in 6 of them. Of the 11 pincer lesion findings, 7 were verified. A moderate level of lameness was noted in 12 patients. A cam lesion was diagnosed in 7 and verified in 4 patients. Of the 5 pincer lesion findings, 3 were verified. The highest level of lameness represented a degree that would mean an inability to complete the test. None of the monitored patients fell into this level.

The last monitored criterion was the stair-climbing test. Completion of the test required climbing eight stairs. Patients were classified into 4 groups. The patients in the first group were able to climb the stairs normally, without assistance; this included 32 patients. Nineteen patients in this group were diagnosed with cam lesions, of which 14 were subsequently verified. A pincer lesion was noted in 13 patients, and 9 cases were confirmed. The second group needed moderate assistance/support. This group included 21 patients, including 10 cases with cam lesions, of which 7 were verified. A pincer lesion was found in 11 and verified in 8 patients. The last evaluated group comprised patients who needed more help to complete the stair-climbing test. Out of a total of 9 patients, a cam lesion was identified in 4 and confirmed in 3 patients. A pincer lesion was recorded in 5 patients and verified in 4. The fourth group would have included patients who would not have been able to complete this test, but there was no one with this characteristic in the monitored sample. In terms of the observed statistical variables, the stair-climbing test proved to be valid for both types of lesions and for all groups of respondents classified according to their stair-climbing ability.

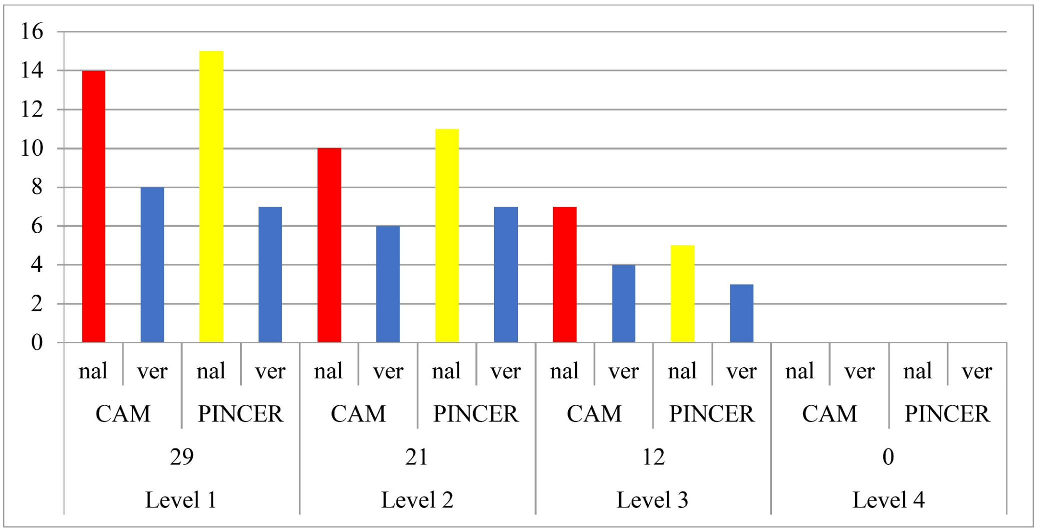

Figure 7. Expression of the number of patients according to the degree of lameness.

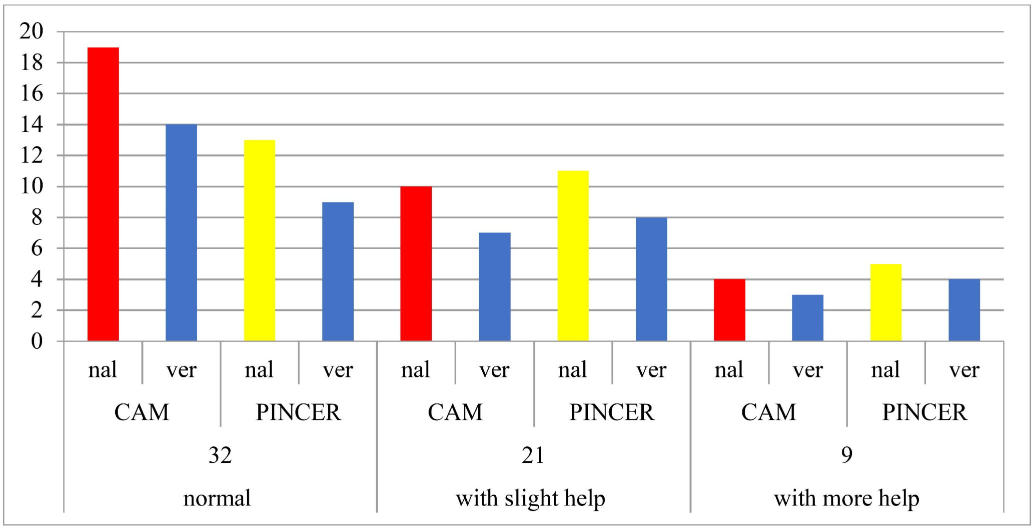

Figure 8. Expression of the number of patients according to the stair walking test.

Discussion

Femoroacetabular impingement syndrome has been studied recently in regard to limb biomechanics involved in everyday activities, with comparisons between patients' affected and contralateral unaffected limbs and non-FAI controls (16). Conservative and arthroscopic approaches were compared in a study that found that arthroscopy led to greater improvement (17). However, a similar comparison in another study (18) produced different results: the greater effectiveness of surgery in comparison with physical therapy was not proven. A comparison of arthroscopy and open surgery found that arthroscopy was contraindicated in patients with severe osteoarthritis (19). All these studies have concluded that it is important to effectively determine the severity of FAI and that early detection of FAI can improve patient prospects (20); therefore, this was our aim in this study.

The positive predictive value—that is, the probability that in the case of a positive test, the patient actually clinically suffers from the given disability—was used to evaluate the quality of the tests. This value is closely related to prevalence: the higher the prevalence, the higher the probability of a positive predictive value must be for the test to be clinically applicable. Given that the sample of patients was not randomly selected from the population, but was a selection sample comprising patients who met the given criteria and especially patients who presented with certain problems, it is necessary for the evaluation of the test that the positive predictive value is sufficiently high. Since there is no universal rule determining the threshold for a good positive predictive value, we chose a value greater than or equal to 80% for this study.

In the FAI group, which included 62 evaluated persons, the data measured by the gyroscope significantly agreed with the results of imaging methods and clinical examinations of the patients. We also evaluated the correlation of the gyroscope measurements with the data given in the patient questionnaire and findings from clinical and paraclinical examinations. We initially assessed patients by use of the modified Harrison questionnaire (Harrison hip score). The signal from the gyroscope was then evaluated by using the Welch method of frequency analysis. The aim of this evaluation was to determine the statistical parameters of the cam or pincer lesion detection test in individual patients on the basis of their results in paraclinical examinations. The results of this study prove that with this method it is possible to appropriately detect the presence of individual types of lesions in full abduction movement and full external rotation in patients with BMI of class 1 and 2 who have up to a moderate degree of soreness. A number of results were burdened by an error in the form of an insufficient number of patients. Despite this fact, it can be stated that the presented method can be used to determine the lesion type and will be part of future research in this area.

The following conclusions follow from the statistical processing. In the case of abduction and abduction movements, the test cannot be used, as they differ from the types of movement that the gyroscope is able to reliably record. The test can be used to detect full external rotation, but due to the nature of the signals recording specific movements and discrepancies, it is not possible to detect full internal rotation or its reduction. An interesting result is the relatively reliable recognition of BMI classes I and II, certainly due to the change in the length of the entire movement. It is not possible to recognize BMI class III, however, because movement in BMI class III does not fundamentally differ from movement in BMI class II. For pain, it was only possible to marginally determine mild pain and unbearable pain, but the latter was reported by only one patient, which is an insufficient sample. Due to the significant perceived subjectivity of pain, our test is not suitable for recognizing the level of pain. Surprisingly, the test failed the limp detection and stair-climbing test. Here it can be assumed that it is appropriate to use data-processing methods other than those used in this particular case. Furthermore, our results prove that the gyroscope is more sensitive to higher degrees of osteoarthritis of the joint, which we attribute to higher friction in degeneratively changed joint structures and the possible expected absence of synovial fluid, which in itself potentiates the higher quality of the measured signal.

Conclusion

In patients diagnosed with FAI (by X-ray or MRI) who completed the experimental study, it was possible to reliably and positively detect changes in movement frequency curves in the affected joint. However, it was not possible to identify a clinical correlation between individual types of FAI disability (cam, pincer, mixed type) from the 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 with the X-ray diagnosis can be seen in the evaluation of 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, it is worth noting the accentuation of the increase in sensitivity and specificity at the lower levels of the pain scale. This fact again supports the use of gyroscope measurements in the possible early detection of asymptomatic patients diagnosed with FAI.

Acknowledgement

The work was supported by the Ministry of Defense of the Czech Republic's "Long Term Organization Development Plan 1011" – Clinical Branches II of the Faculty of Military Health Sciences Hradec Kralove, University of Defense, Czech Republic.

Conflict of Interest

The authors declare that they have no conflicts of interest regarding the publication of this article.

References

1. Glyn-Jones, S, Palmer, AJR. Osteoarthritis. The Lancet. 2015;386:376-387.
2. Matsumoto K, Ganz R, Khanduja V. The history of femoroacetabular impingement. Bone Jt. Res. 2020;9:572-577.
3. Emary P. Femoroacetabular impingement syndrome: a narrative review for the chiropractor. J. Can. Chiropr. Assoc. 2010;54:164.
4. Kuhns BD, Frank RM, Pulido L. Open and arthroscopic surgical treatment of femoroacetabular impingement. Front. Surg. 2015;2:63.
5. Zhang D, Chen L, Wang G. Hip arthroscopy versus open surgical dislocation for femoroacetabular impingement: a systematic review and meta-analysis. Medicine. 2016;95:41.
6. Rafi M, Kautzner J, Havel O, et al. Benefits of the Acetabular Microfracture Technique in Arthroscopic Treatment of Chondral Defects in Femoroacetabular Impingement Syndrome: Two-Year Results of a Multicenter Prospective Randomized Study. Acta Chir Orthop Traumatol Cech. 84, 2021;88:18–37
7. Byrd JT (Ed.). Operative hip arthroscopy. Springer Science & Business Media, 2012.
8. Swagerty DL, Hellinger D. Radiographic assessment of osteoarthritis. Am Fam Physician. 2001;64:279.
9. Khan W, Khan M, Alradwan H, et al. Utility of intra-articular hip injections for femoroacetabular impingement: a systematic review. Orthop. J. Sports Med. 2015;3: 2325967115601030.
10. Ayeni OR, Chan K, Al-Asiri J, et al. Sources and quality of literature addressing femoroacetabular impingement. Knee Surg. Sports Traumatol. Arthrosc. 2013;21:415-419.
11. Abellàn J, Esparza F, Blanco A, et al. Radiological evidence of femoroacetabular impingement in asymptomatic athletes. Br J Sports Med. 2011;454:333-333.
12. Frank JM, Harris JD, Erickson BJ, et al. Prevalence of Femoroacetabular Impingement Imaging Findings in Asymptomatic Volunteers: A Systematic Review. J. Arthrosc. Relat. Surg. 2015;31:1199-1204.
13. Lee TF, Lin WC, Wu LF, et al. Analysis of vibroarthrographic signals for knee osteoarthritis diagnosis. In 2012 Sixth International Conference on Genetic and Evolutionary Computing 2012;223-228.
14. Cimr D, Studnicka F, Fujita H, et al. Application of mechanical trigger for unobtrusive detection of respiratory disorders from body recoil micro-movements. Comput Methods Programs Biomed. 2021;207:106149.
15. Studnička F. Analysis of biomedical signals using differential geometry invariants. Acta Phys. Pol. 2011;12170:6A.
16. King MW, Lawerenson PR, Semciw AI, et al. Lower limb biomechanics in femoroacetabular impingement syndrome: a systematic review and meta-analysis. British Journal of Sports Medicine 2018;52:566-580.
17. Griffin DR et al. Hip arthroscopy versus best conservative care for the treatment of femoroacetabular impingement syndrome (UK FASHIoN): a multicentre randomised controlled trial 2021, Lancet, 391,10136.
18. Mansell NS, Rhon DI, Meyer J, et al. Arthroscopic Surgery or Physical Therapy for Patients With Femoroacetabular Impingement Syndrome: A Randomized Controlled Trial With 2-Year Follow-up. The American Journal of Sports Medicine. 2018;46(6):1306-1314.
19. Papalia R, Del Buono A, Franceschi F, et al. Femoroacetabular impingement syndrome management: arthroscopy or open surgery?. International Orthopaedics (SICOT) 2012;36:903–914.
20. Khan M, Bedi A, Fu F, et al. New perspectives on femoroacetabular impingement syndrome. Nat Rev Rheumatol 2016;12:303–310.