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Mathematical Modeling of Indications for Reconstructive Surgery of the Hip Joints in Patients with Cerebral Palsy

Yatsuliak M.B.[1] ✉

Summary. Relevance. *Early detection of hip pathology in patients with cerebral palsy is an effective way to prevent spastic hip dislocation.* ***Objective:*** *to improve the diagnosis of diseases of the hip joints in cerebral palsy through the clinical and radiographic screening based on mathematical modeling.* ***Materials and Methods.*** *The total number of patients was 47 (86 joints). We carried out a clinical and radiographometric examination of the hip joints with our own method and using standard anteroposterior radiographs, which were used to determine the parameters of the hip joint. Mathematical modeling of indications for reconstructive surgery using logistic regression was also performed.* ***Results.*** *The mathematical model "probability of indications for surgical interventions" was developed on the basis of the studied indicators and factors of influence.* ***Conclusions.*** *A mathematical model for screening of hip joints based on the acetabular angle (AA), neck-shaft angle (NSA), femoral torsion (FT), migration percentage (MP), gross motor function classification system (GMFCS) level, gait, and age is proposed; the accuracy of 90.6% is valid for establishing correct indications for surgery (the critical level of indicators is >16.95° for AA, >45° for FT, > 141.63° for NSA, >30 % for MP, and ≤11 years for age).*

Key words: *cerebral palsy; mathematical modeling; femoral torsion; migration percentage; hip joint screening.*

Introduction

The lack of clear protocols for the treatment and diagnosis of hip diseases in patients with cerebral palsy (CP), as well as simple screening systems that can be used by primary care professionals in Ukraine prompted us to write this article. Improper formation of the hip joint (HJ) combined with increased muscle tone leads to decentration of the femoral head and progression of HJ instability.

We have to work with a large number of advanced cases due to the small number of pediatric orthopedists who specialize in treatment of patients with cerebral palsy. Patients are observed by neurologists who do not have the skills of

clinical and radiological assessment of the state of the hip joint. Some medical institutions and rehabilitation centers are supervised by doctors of the Department of joint diseases in children and adolescents of the Institute of Traumatology and Orthopedics of the National Academy of Medical Sciences of Ukraine to minimize or prevent complications related to the hip joint.

Hip displacement progresses without significant clinical manifestations, and when it does occur, it can cause pain and decreased HJ movement in patients with CP. There are difficulties with personal care, sitting, standing, and ambulation. Many authors claim that HJ monitoring programs are able to prevent hip dislocation [1] and are quite effective [2].

There is a connection between the deformation of the proximal femur and hip displacement [3]. There is a significant dynamic effect of compensation mechanisms that should be considered when assessing femoral torsion (FT) [4]. Most modern HJ screening systems in cerebral palsy are based on the migration percentage (MP) [5]. They diagnose hip displacement and note the dynamics of the process but do not yield accurate HJ parameters.

The objective of the study was to improve the diagnosis of diseases of the hip joints in cerebral palsy using clinical and radiographometric screening based on mathematical modeling.

Materials and Methods

We carried out an analysis of clinical cases of 47 patients (86 joints) with pathology of the hip joints in CP, who had been treated in the State Institution "Institute of Traumatology and Orthopedics of the National Academy of Medical Sciences of Ukraine" during 2018-2021. The gender of the patient was not taken into account because previous studies did not report significant inter-gender differences [6]. No patient had

✉ *Yatsuliak M.B., myhail52368@gmail.com*
[1]*SI "Institute of Traumatology and Orthopedics of NAMS of Ukraine", Kyiv*

a history of bone surgery. We developed a mathematical model based on the true HJ parameters: femoral neck-shaft angle (NSA), femoral torsion (FT), acetabular angle (AA) and migration percentage (MP), as they can be changed during surgery.

The informativeness of the factors taken into account by surgeon when choosing therapeutic tactics was also clarified: age, Gross Motor Function Classification System (GMFCS) level [7], ambulatory status (ambulating, non-ambulating). The age of patients ranged within 3-30 years: up to 4 years (5 patients), 4-6 years (10 patients), 7-9 years (10 patients), 10-12 years (8 patients), 13-16 years patients (13 patients), and 30 years (1 patient). According to the GMFCS, level II was observed in 11 patients, level III – in 16 patients, level IV – in 12 patients.

The sample in this study included mainly patients with spastic tetraparesis (30 patients), spastic paraparesis (9 patients), and hemiparesis (8 patients). Each hip joint was evaluated separately; in patients with hemiparesis, only the ipsilateral side was taken into account. 33 of our patients were ambulating, and 14 patients were non-ambulating at the moment of the examination but were considered promising in terms of verticalization, or gait function was lost due to spastic hip dislocation. 8 patients had a history of adductor myotomy in the local medical facilities. Hip radiographs performed at the age of 3 months were preserved in 15 patients: 8 patients were diagnosed with developmental dysplasia of the hip and 7 patients were born with normal hips. Data on whether developmental dysplasia had been treated before the age of 1 year were not taken into account due to their absence.

All patients underwent clinical evaluation of FT according to Ruwe [8], standard anterior-posterior HJ radiograph (standard positioning [SP]), posterior-anterior HJ radiograph using positioning according to our own method (PATOOM) that yielded the true parameters [9, 10]. The absence of significant differences in AA ($p > 0.05$), determined in both positionings, as well as high accuracy of FT and NSA measurement during PATOOM comparing to intraoperative data, were described in our previous works [11].

Statistical data processing was performed using statistical software STATISTICA 7.0, MedCalc Statical Software v.11.5.0.0. using the χ^2 test, multiple logistic regression (with calculation of the odds ratio (OR) and 95% confidence interval (95% CI)), and ROC analysis with an estimate of the area under the curve (AUC).

Depending on the type and nature of the data distribution, the appropriate statistical criterion was chosen to assess the reliability of the influence of the factor. For parameters that had a normal distribution, parametric methods of statistical evaluation were used. Discrepancies were considered significant when the significance level $p < 0.05$ was reached.

In the study, the results of the analysis are presented as distributions of clinical parameters (%), arithmetic mean, and standard deviation ($M \pm SD$). Inter-group comparisons were performed using the Chi-square test and one-way analysis of variance (ANOVA) for the respective data types. Spearman's correlation coefficient was used to estimate the relationship between radiographometric parameters and other factors. To study the prognostic factors, multiple logistic regression was utilized using step-by-step exclusion of uninformative indicators to leave only significant independent variables in the final model. Critical value, sensitivity and specificity of an indicator were assessed using ROC analysis.

Results

The subjects of the study were the hip joints in patients with cerebral palsy. Most patients had stable hips and were able to ambulate; 23 hips had MP > 33%. We divided patients into those who had indications for HJ reconstructive surgery and persons who did not have these indications at the moment of the examination. Out of reconstructive surgeries, intertrochanteric proximal femoral derotational osteotomies were performed, combined if necessary with variization and shortening, as well as pelvic osteotomies. No more detailed division was carried out, since this was not our goal.

To create a mathematical model, we used the true HJ parameters, obtained during PATOOM, and the factors that we take into account while making decision concerning surgical treatment. The data was analyzed and refined, and good results were obtained. When we inserted into the formula the migration percentage obtained in SP according to the author's method [5], the accuracy of the model improved even more.

Mathematical model of indications for hip surgery in patients with cerebral palsy:

Y – probability of indications for the surgery

Y = 0.051 × AA – 0.453 × GMFCS – 0.238 × Age + 0.084 × migration percentage (SP) + 0.271 × FT + 0.92 × Ambulation – 0.122 × NSA + 4.142

Chi-square = 52.12, $p < 0.001$.

The accuracy of the model is 90.6%. Belonging to group 0 – "No indications for surgery" – is determined by the model with an accuracy of 77.78%, and belonging to group 1 – "There are indications for surgery" – with an accuracy of 96.55%; the area under the curve AUC = 0.934 (0.859-0.977); chi-square = 52.12 ($P < 0.001$). The model has a very good predictive power, which indicates a good estimate of the probability of indications for surgery.

The model is based on data of 47 patients (85 joints); of them, 27 (31.8%) joints had no indications for surgery and 58 (68.2%) joints had indications for surgery. 7 indicators were taken to find out which indicators are the most or less informative. The most informative ones were as follows: age, MP (SP), and FT. However, as the full formula adds 5% accuracy with the indicators (GMFCS, NSA, AA, and ambulation), it was decided to leave them. Therefore, we decided to stay on the expanded version of the formula.

We determined the migration percentage index in both positionings. Based on these data, we developed a mathematical dependence using regression modeling to calculate the MP in the standard positioning based on the MP (PATOOM):

Migration percentage (SP) = 1.11 × migrant percentage (PATOOM) + 0.44

$R = 0.89$, $R2 = 0.797$, $F (1.84) = 330.04$, $p < 0.001$.

Simplified version of the mathematical model that can be used for total HJ screening in CP:

Y – probability of indications for the surgery

Y = 0.078 × Migration percentage (SP) + 0.227 × FT – 0.203 × Age – 10.45

Chi-square = 47.8, $p < 0.001$.

The accuracy of the model is 87.06%. Belonging to group 0 – "No indications for surgery" – is determined by the model with an accuracy of 74.07%, and belonging to group 1 – "There are indications for surgery" – with an accuracy of 93.1%; the area under the curve AUC = 0.917 (0.837-0.966); chi-square = 47.8 ($P < 0.001$). The model has a very good predictive power, which indicates a good estimate of the probability of indications for surgery.

Discussion

To develop a mathematical model of HJ screening, we studied clinical cases and used radiographs of patients who were referred to us for specialized care. Some patients did not ambulate on their own but are considered as promising in terms of verticalization. The older age groups were dominated by patients who could ambulate independently. GMFCS level IV was less common in older patients.

Our proposed mathematical model has a good accuracy (90.6%). In this case, the model determines "presence of indications for surgery" with an accuracy of 96.55%, and "absence of indications for surgery" is determined by the model with an accuracy of 77.78%, which in our opinion is due to the fact that pathological changes in HJ parameters are observed in most patients with CP, but these patients not always require surgical correction. Reconstructive surgery was sometimes not recommended in elderly patients due to the risk of ambulation loss and sometimes due to incorrect adductor myotomy.

There are likely to be other risk factors – such as the range of HJ mobility, the degree of spasticity, and the CP subtypes – that should be considered while making decision on the treatment of an individual child [12].

The critical level of AA, when indications for surgery were detected, was > 16.95° (Fig. 1a). The critical level of NSA, when indications for surgery were detected, was > 141.63° (Fig. 1b). The critical level of FT, when indications for surgery were detected, was > 45° (Fig. 1c). The critical level of the migration percentage, when indications for surgery were detected, was > 30% (Fig. 1d). The critical age level of patients with CP, when indications for surgery were detected, was ≤ 11 years (Fig. 1e).

We do not pay much attention to the critical level of AA in this model due to the fact that proximal femoral osteotomies were performed in all patients with indications for surgery and pelvic osteotomies were used selectively in AA above age norms. Therefore, an increase in the critical level of AA in this case has a lower value, in contrast to NSA, FT and migration percentage, which have been always corrected during surgery. Early detection of HJ pathology in CP can limit the surgery to proximal femoral osteotomies, since pathological changes in the acetabulum appear later [13]. Particular attention should be paid to patients with CP who have developmental dysplasia of the hip [14].

The full version of the formula should be used by orthopedic surgeons in the specialized hospitals, where the precise HJ parameters will help determine the tactics of surgical treatment.

A simplified version of the mathematical model is proposed for primary care physicians, who then refer patients with CP to medical specialists. By mastering the method of clinical determination of FT [8], migration percentage [5] and knowing the age of the child, a primary care specialist will be able to detect surgical pathology with an accuracy of 87.06%.

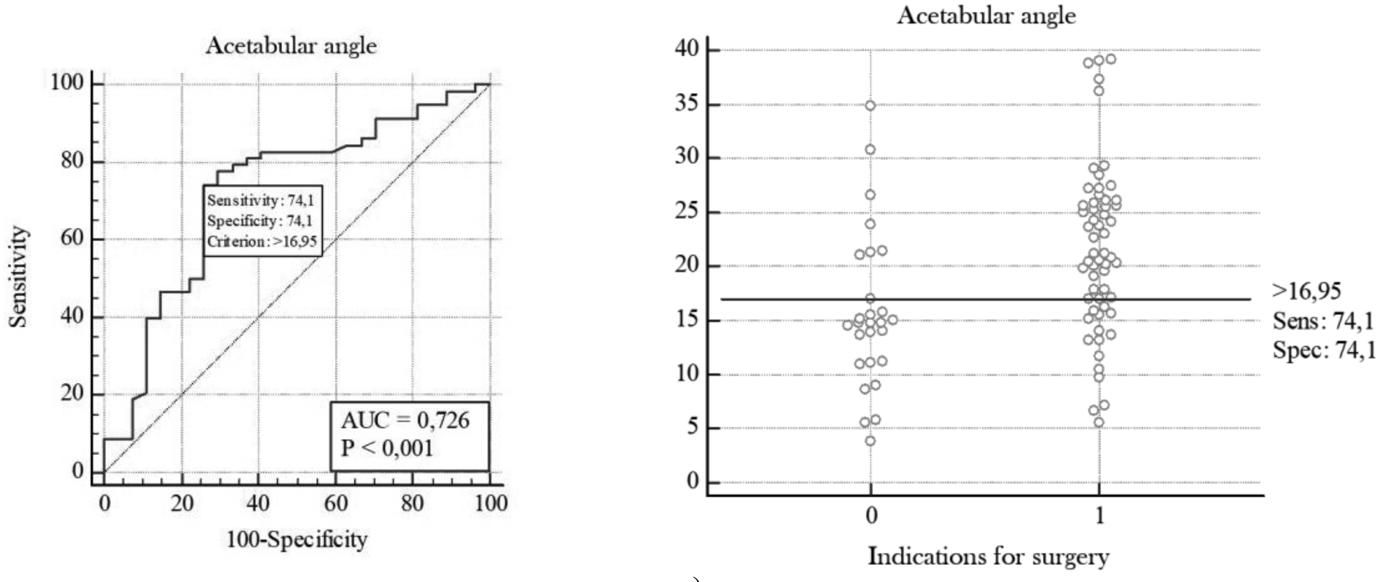
We did not include in this study patients with mild forms of CP (GMFCS level I) because pathological changes are very rare in this case and patients with severe forms (GMFCS level V) because in these patients palliative surgery is replaced by reconstructive one.

Countries that have introduced HJ screening systems for CP at the state level (Australia, Sweden, Canada, and the United States) report good results now.

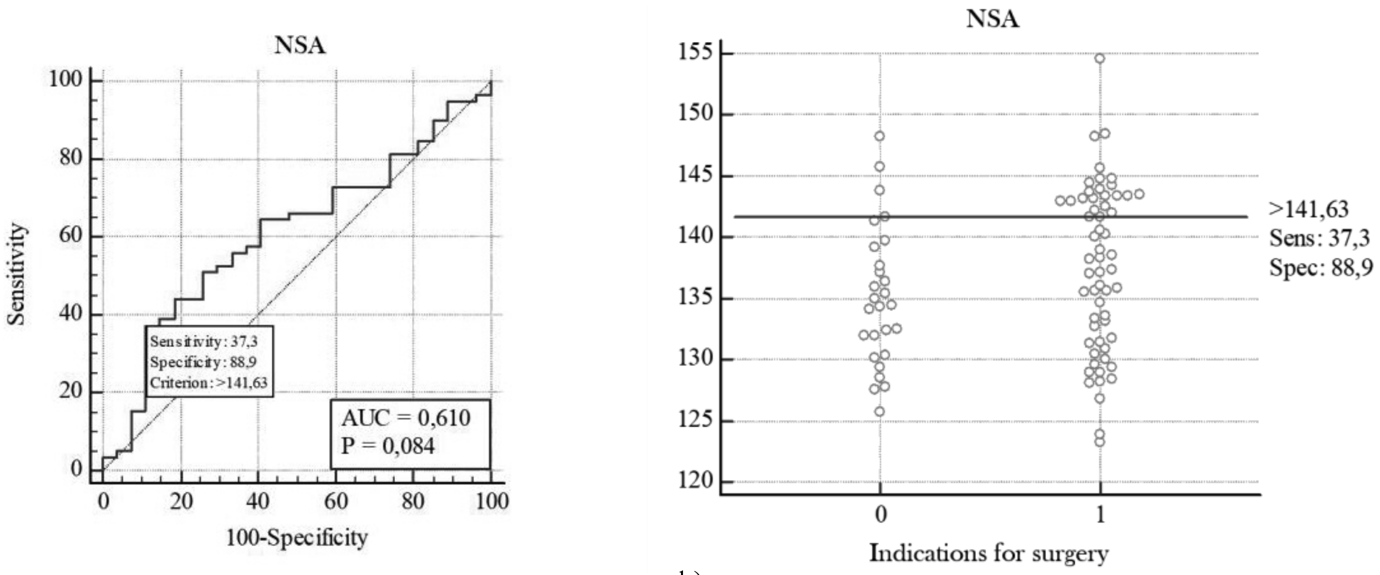
Our model does not answer the question which type of hip surgery should be performed in patients with CP, nonetheless it allows patients to be sorted by primary care specialists and referred to specialized medical institutions. The tactics of surgical treatment should be selected individually for each child.

Conclusions

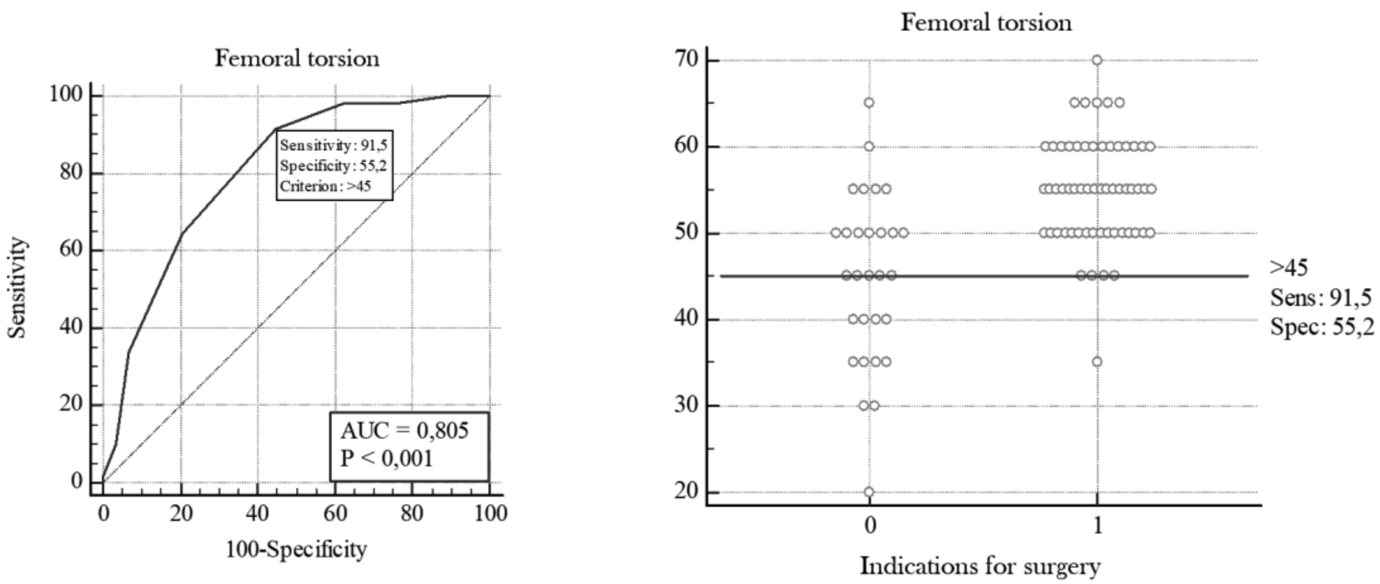
We developed a mathematical model to determine the indications for hip surgery in patients with cerebral palsy based on AA, NSA, FT, MP, GMFCS, ambulation, and age; the accuracy of the model is 90.6%, which can be used for screening. The critical level, when indications for surgery were detected, is > 16.95


Acetabular angle
Sensitivity
100-Specificity
Sensitivity: 74,1
Specificity: 74,1
Criterion: >16,95
AUC = 0,726
P < 0,001
Acetabular angle
>16,95
Sens: 74,1
Spec: 74,1
Indications for surgery

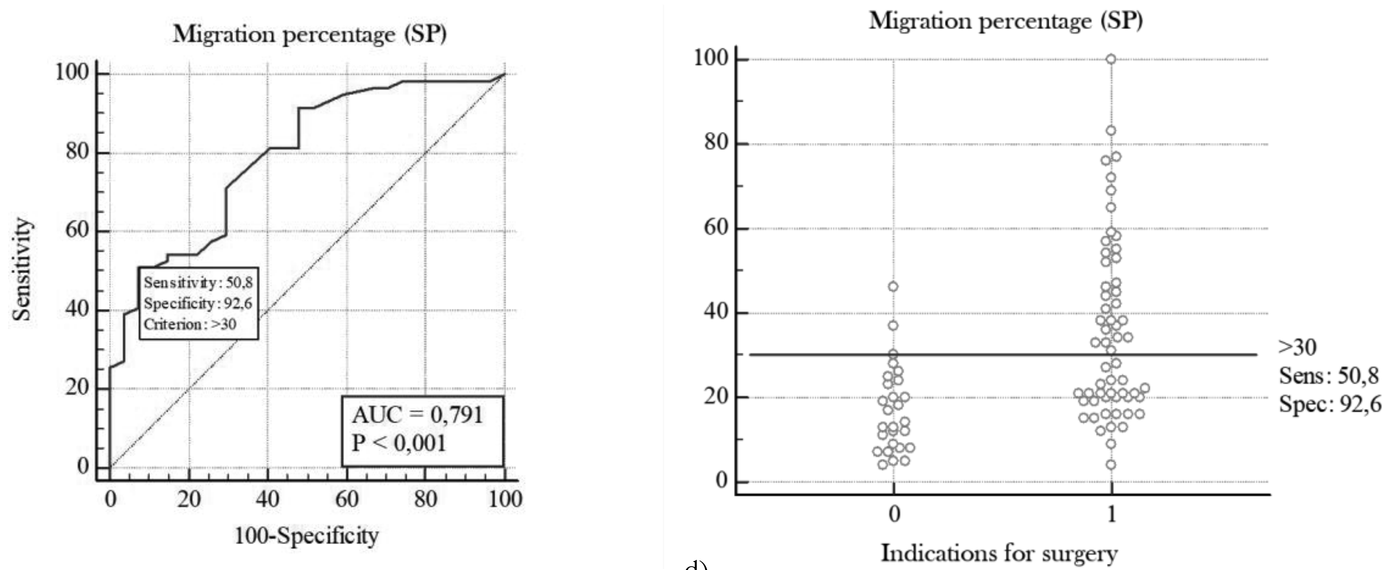
a)


NSA
Sensitivity
100-Specificity
Sensitivity: 37,3
Specificity: 88,9
Criterion: >141,63
AUC = 0,610
P = 0,084
NSA
>141,63
Sens: 37,3
Spec: 88,9
Indications for surgery

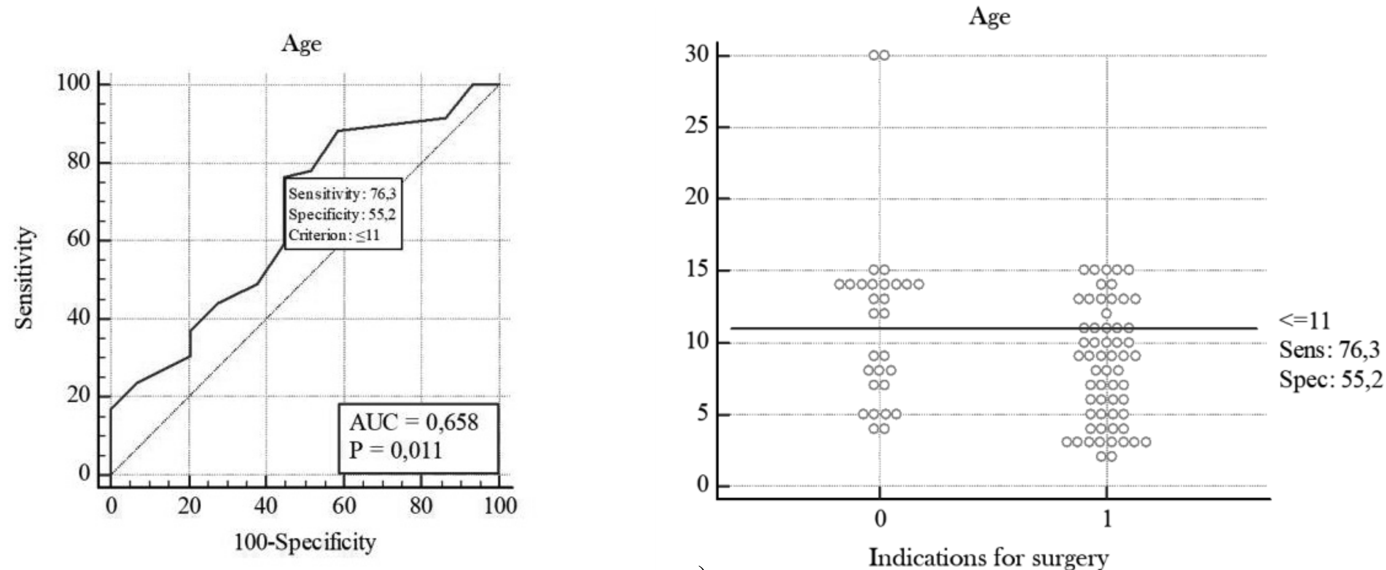
b)


Femoral torsion
Sensitivity
100-Specificity
Sensitivity: 91,5
Specificity: 55,2
Criterion: >45
AUC = 0,805
P < 0,001
Femoral torsion
>45
Sens: 91,5
Spec: 55,2
Indications for surgery

c)



d)



e)

Fig. 1a, b, c, d, e. ROC analysis to determine the prognostic value of indicators concerning the probability of detection of surgery indications in patients with CP. Critical level of parameters for the two groups (“No indications for surgery” – 0; “There are indications for surgery” – 1) is based on: acetabular angle (a), neck-shaft angle (b), femoral torsion (c), migration percentage (d), age (e)

° for AA, > 45° for FT, > 141.63° for NSA, > 30% for MP, ≤ 11 years for age.

Conflict of interest. The authors declare no conflict of interest in the preparation of this article.

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Математичне моделювання показань до реконструктивної хірургії кульшових суглобів у пацієнтів із ДЦП

Яцуляк М.Б.[1]
[1]ДУ "Інститут травматології та ортопедії НАМН України", м. Київ

Резюме. Актуальність. *Раннє виявлення патології кульшового суглоба у пацієнтів із дитячим церебральним паралічем є дієвим способом запобігання спастичному вивиху стегна.* ***Мета дослідження.*** *Покращити діагностику патології кульшових суглобів при дитячому церебральному паралічі шляхом створення клініко-рентгенограмометричного скринінгу на основі математичного моделювання.* ***Матеріали і методи.*** *Загальна кількість пацієнтів становила 47 осіб (86 суглобів). Нами проведено клініко-рентгенограмометричне обстеження кульшових суглобів власним способом та стандартні передньо-задні рентгенограми, за якими визначали параметри кульшового суглоба. Математичне моделювання показань до реконструктивної хірургії проведено за допомогою логістичної регресії.* ***Результати.*** *Створено математичну модель "ймовірність показань до оперативних втручань" на основі досліджених показників та факторів впливу.* ***Висновки.*** *Запропонована математична модель для скринінгу кульшових суглобів на основі ацетабулярного кута (АК), шийково-діафізарного кута (ШДК), торсії стегнової кістки (ТСК), індексу Реймерса (ІР), шкали великих рухових розладів (GMFCS), ходи, віку, з точністю 90,6% є валідною для встановлення коректних показань до операції (критичний рівень показників становить для АК >16.95°, для ТСК >45°, для ШДК >141,63°, ІР >30%, вік ≤11 років).*

Ключові слова: *дитячий церебральний параліч; математичне моделювання; торсія стегнової кістки; індекс Реймерса; скринінг кульшового суглоба.*