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تطبيق المنطق الضبابي من النمط الثاني في بناء مؤشر رقمي لتقييم التدخل الجراحي لأطفال الشلل الدماغي التشنجي

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تاريخ الايداع
تاريخ القبول

الملخص:

تحليل المشية له العديد من التطبيقات في التقييم الكمي لمشية الإنسان الطبيعية أو المرضية. يتم حساب العديد من المحددات في مراقبة المشية بما في ذلك بارامترات المسافة الزمن، المحددات الحركية، والمحددات التحريكية للمفاصل لتقييم مشية المريض بشكل عددي أو بناء على مقياس ما. في هذا البحث، تم استخدام نظام المنطق الضبابي من النوع الثاني Fuzzy logic type-2 لتصميم مؤشر ذكي(FL2-AKHDI) يقيّم انحرافات مفاصل الكاحل والركبة والورك لدى مرضى الشلل الدماغي قبل وبعد الجراحة مقارنة بالأطفال الذين يتطورون بشكل طبيعي. تبدأ المنهجية المقترحة باستخراج السمات المميزة من مخططات زوايا مفاصل الورك والركبة والكاحل خلال دورة المشي، ثم تهيئة نظام FL بناءً على الميزات المستخرجة. وأخيراً، تقييم أداء المؤشر المقترح. وخلصت النتائج إلى أنه من الممكن استخدام المنطق الضبابي من النوع الثاني في تقييم فعالية العمليات الجراحية لمرضى الشلل الدماغي، حيث انخفضت القيمة المتوسطة للمؤشر لمجموعة المرضى بنسبة (25%)، وتتوافق تلك النسبة مع نسبة الانخفاض في القيمة المتوسطة لمؤشر GPS والتي تساوي (21%). كما وتأتي أهمية هذا البحث في تقديم نموذجاً أولياً لنظام دعم القرار الطبي الذي يمكنه تقييم الحالات المرضية بشكل كمي، وكذلك تقييم كفاءة العلاج والتدخل الطبي باستخدام FL.

الكلمات المفتاحية: تحليل المشية، الشلل الدماغي التشنجي، المنطق الضبابي.

Application of Fuzzy Logic type 2 in Building a Numerical Index for Evaluating Surgical Intervention for Children with Spastic Cerebral Palsy

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Abstract:

Gait analysis has many applications in the quantitative assessment of normal or pathological human gait. Many parameters are calculated in gait monitoring, including spatiotemporal, kinematic, and joint kinematic parameters to evaluate the patient's gait numerically or based on a scale. In this research, a Fuzzy logic type-2 system was used To design a smart index (FL2-AKHDI) that evaluates the deviations of the ankle, knee, and hip joints in CP patients before and after surgery compared to children with normal development. The proposed methodology starts by extracting the characteristic features from the angle diagrams of the hip, knee, and ankle joints during the gait cycle. Then it initializes the FL system based on the extracted features. Finally, the performance of the proposed index will be evaluated. The results concluded that it is possible to use Fuzzy logic type-2 to evaluate the effectiveness of surgical operations for patients with cerebral palsy The average value of the index for the patient group decreased by (25%), and this percentage corresponds to the percentage of decrease in the average value of the GPS index, which is equal to (21%). The importance of this research also lies in providing a prototype of a medical decision support system that can quantitatively evaluate disease conditions and evaluate the efficiency of treatment and medical intervention using FL.

Keywords: Gait Analysis, Spastic Cerebral Palsy, Fuzzy Logic.

1- Introduction

Damage to the brain (central nervous system) in patients with cerebral palsy causes incorrect movement control (Kawamura et.al., 2007) resulting in a complex walking deformity, and it is challenging to identify this deformity through a traditional physical examination or visual vision alone (Ajagadamma et.al., 2010) so it has become computerized gait analysis is an urgent necessity, as it adds quantitative measurements that include a large set of data that gives a definition of gait deviations and a better understanding of them, which helps in developing the most appropriate treatment plan and then evaluating the results of treatment and the amount of improvement in walking (Armand et.al., 2016).

By using gait analysis many parameters, including spatio-temporal and kinematic parameters, are calculated to assess the patient's gait numerically or on a scale (Khalaf et.al., 2022). The existence of numerous parameters, as well as the uncertainty associated with each parameter, makes accurately assessing a patient's gait difficult. Furthermore, comparing results for a particular patient at various times or clinical points makes determining treatment efficacy difficult.

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Accordingly, data complexity hampered the clinical use of gait analysis in many clinical trials, raising awareness of the need for a summary index, a single measure of the quality of human gait pattern that addresses the maximum number of gait parameters that have the greatest impact on medical diagnosis (Rosati et.al., 2017).

Accordingly, considerable effort has been expended in developing indices that summarize and condense the information derived from many gait parameters as a result of gait analysis into a singular score.

Fuzzy logic (FL) is one of the most reliable artificial intelligence tools in evaluating and classifying human gait due to its ability to mimic human reasoning. FL produces accurate outputs by using reasoning methods based on a set of inputs and knowledge bases that represent the human expert. Moreover, it enables accurate gait evaluation and assists clinicians in understanding the mechanism of gait. (Massoud, R. (2022)

The application of fuzzy logic in the clinical studies of human gait is still rare. On the other hand, studies have shown that it can deal with the large number of parameters studied in gait analysis and the possibility of assembling and expressing them according to a semantic expression that describes the degree of weakness or deviation in human gait.

Researchers have begun to use a Type 2 fuzzy logic system (Type 2 FLS) in gait classification because it can model uncertainties in gait patterns and deal with noise in measured gait data. The researchers used Type 2 FLS relying on four features derived from kinematics and EMG data to build a gait classification system to recognize the gait patterns of healthy people with reconstructed anterior cruciate ligament (ACL-R). Type 2 FLS outperforms Type 1 FLS in terms of classification accuracy (Massoud, 2022).

Cerebral palsy (CP) is the most prevalent motor impairment in childhood. Cerebral palsy is a collection of diseases that impair a person's ability to move, balance, and keep equilibrium. Spastic CP (SCP) refers to the damage or issue in the motor cortex of the brain. Where the motor cortex is in charge of action planning and regulation, a SCP kid suffers from gait impairment and instability (Rosenbaum, 2003). The worldwide incidence of cerebral palsy is approximately 2 to 4 per 1,000 live births. In India, it is estimated at 3 cases per 1000 live births (Gupta, 2023).

This percentage varies from one country to another and also varies in the same country from one time period to another (Ajagadamma et.al., 2010). Spastic cerebral palsy (SCP) is considered the most common type of cerebral palsy, as its incidence exceeds (70%) of cerebral palsy patients (Stanley et.al., 2006). It occurs when the brain injury is in the cerebral cortex (Al-Gabbani, 2006), causing neuromuscular motor problems in patients in which spasticity is the dominant clinical feature (Whittle, 2007).

Recently, (Al-Mawaldi and Khadour, 2022) presented a clinical study involving gait analysis of SPC and healthy children. The study included 10 individuals with spastic CP who endured (SEMLS) at the age of (9.2±3.2) years. And a set of 10 healthy children aged (8.2±2.2) years. They compared kinematic parameters such as Gait Profile Score (GPS) before and after Single Event Multilevel Surgery (SEMLS) on walking for Spastic Cerebral Palsy children.

2-Research objective

This research aims to assess the effect of surgeries on children with cerebral palsy, using fuzzy logic type-2 by building a digital index to assess the degree of deviation of the hip, knee and ankle joints (FL2-AKHDI) before and after surgical operations for children with cerebral palsy. Each joint is evaluated with a subsystem fuzzy logic that takes into account the important angles of the gait cycle and the times of its occurrence. Then the fuzzy systems are collected for each of the joints using a final fuzzy system that gives in its output a digital value to the deviation of the hip, knee and ankle joints.

3-Reference studies

Fuzzy logic shows a high potential in gait classification. Because fuzzy algorithm translates the experiences of experts into objective rules that trigger based on subject data. Studies built fuzzy logic inference systems based on gait kinematic, kinetic, or time distance parameters (Darbandi et.al., 2020). (Massoud et .al, 2023) utilized a fuzzy inference system based on ground reaction force to determine the severity of spastic cerebral palsy in 10 children. The system output is a percent that represents the severity of the examined subject and how much is close to being healthy (0%) and severe SCP (100%).

(Rosati et.al., 2017) proposed a new index to evaluate the level of gait impairment of a patient based on fuzzy logic. The proposal is a compilation of two Fuzzy Inference Systems (FISs) where one system uses gait phases (GP) (referred to as FIS-GP) to evaluate gait and the other system relies on knee joint kinematics (JK) and is referred to as FIS-JK.

Two groups of samples were used, one of which was used for training and building the system (FISs), and it consisted of thirty people who did not suffer from any neurological or movement diseases that could affect their gait. The other group is to test and verify the validity of the proposal and includes (twelve healthy people - five people with an artificial hip and two people with poor muscle control).

The result was validated by comparing analyses of two gait analysis experts on a group of 12 people, some of whom had gait disorders and others did not.

The study concluded by comparing the three classifications (of the proposed system and the two human experts) to show that the system gives the same result given by the human expert (Rosati et.al., 2017).

In her master's thesis at an Italian university, (Colaci, 2020) adopted the electromyogram approach in analyzing gait and concluded an indicator that links gait deviation with the asymmetry of the electrical signal of the muscles (EMG). Data of five markers extracted from the EMG signal of four individuals were collected and classified according to the fuzzy logic controller and then divided into the training set and the testing set (respectively 75% and 25%) to be processed by reinforcement and non-reinforcement learning algorithms for prediction. level of inconsistency.

The researcher built the fuzzy rules in this study by applying hierarchical clustering algorithms calculated for each class. With the use of the min-max rule to obtain each value in the interval (0 – 1), some of the membership functions were triangular in shape and others were trapezoidal.

The researcher (Colaci, 2020) concluded the results by determining the muscle asymmetry index and studying its effect on changing walking parameters. However, her study lacked sufficient precision because the data model was not combined with other information explaining the condition of the patients who were studied.

On the other hand, (Massoud, 2022) presented a smart indicator that numerically evaluates the deviations of walking in high heels. The Index was created using a type-2 fuzzy logic system based on the natural state (barefoot).

The study samples were 14 young female students from the University of Damascus, all of whom had a moderate level of physical activity, with no health problems that may affect their gait. The experiments were conducted in the biomechanics laboratory at the University of Damascus using a system of six motion capture cameras with infrared sensors and two force plates.

The proposed system is based on spatiotemporal parameters of normal walking. Therefore, its importance goes beyond the benefit of detecting heel height and its effect on gait, as the index can also be used to evaluate cases of pathological gait deviation or gait deviations due to traumatic injuries in orthopedic and rehabilitation centers for patients with gait deviation. The research results indicated that the swing time, stance time, double support time, stride time, and stride width increase with increasing heel height.

4-Methodology

4-1- Data collection

4-1-1 Data used to build the index

To build the fuzzy logic system, the kinematic parameters of the gait of typically developing healthy children were collected from the Biomechanics Laboratory in the Department of Medical Engineering at Damascus University using the SMART-D Motion Capture System, in addition to the kinematic data from the literature. Table 1 shows the data for healthy children whose kinematic data was used to build the (FL2-AKHDI).

Table 1. includes the data for the children that were used to build the fuzzy

Researcher's name	Year	N. OF children	Age (year) (SD)	Height (cm) (SD)	Weight (kg) (SD)	Gender
Katharine J et.al [25]	2002	10	7.8 ±2.5	-	-	-
Manuela Galli et.al [26]	2010	15	9.2 ±5.7	130.3 ±7.1	33.5 ±9.4	6 M 9 F
Veronica Cimolin et.al [27]	2010	15	8.9 ±3.8	128.6 ±7.4	29.8 ±7.7	7 M 8 F
Meta N Eek et.al [28]	2017	10	10.7 ±1.9	148 ±11	35.1 ±7.4	5 M 5 F
Al-Mawaldi & Khadour [20]	2022	10	8.9 ±2.9	128 ±16.7	26.6 ±11.4	7 M 5 F

4-1-2 Data used in testing the indicator

Three datasets were used to test and evaluate the performance of the (FL2-AKHDI):

First dataset

The angle values and their occurrence times were used for five new reference studies in Table 2, different from the studies in Table 1 that were used in constructing the fuzzy system for typically developing children, taking into account that data of age, height, and weight are close to the data of the children whose kinematic data were used to build the fuzzy system.

Table2. includes characteristics of healthy children in studies that were used to evaluate the fuzzy system.

Researcher's name	Year	N. OF children	Age (year) (SD)	Height (cm) (SD)	Weight (kg) (SD)	Gender
Stansfield et.al [29]	2005	16	9.55 ±1.41	138 ±11	32.64 ±8.07	8 M 8 F
Victoria et.al [30]	2006	12	8 ±0.53	129 ± 9	27.86 ±6.03	7 M 5 F
Katarzyna et.al [31]	2019	8	8.11 ±1.17	125 ±5	26.57 ±8.14	-
Ye ma et.al [32]	2019	10	7.9 ±1.4	132 ±11	26.8 ±6.3	5 M 5 F
Jurgita et.al [33]	2022	17	7.88 ±1.97	131 ±11	28.75 ±7.41	6 M 11 F

Second dataset

The angles and their times of occurrence were used for a sample of 10 healthy children who were used in the research (Al-Mawaldi &Khadour, 2022) whose average age is 8 years, average weight is 26 kg, and average height is 129 cm.

Third dataset

In the end, the angle values for ten children with cerebral palsy were taken from the reference (Al-Mawaldi &Khadour, 2022), whose average age is 8.8 years, average weight is 23.2 kg, and average height is 120.3 cm. Multi-level surgeries were performed on children with cerebral palsy in this dataset to improve their gait. Table 3 shows the operations performed on these children, whether on one limb or both limbs.

Table 3. Shows the operations performed on children with cerebral palsy (Al-Mawaldi &Khadour, 2022).

ID	Type of surgery
Cp1	Lengthening the tendons of the knee joint for both limbs, amputation of the rectus femoris for both limbs and amputation of the hip adductor muscles for both limbs.
Cp2	Achilles tendon lengthening of the right limb, rectus femoris muscle biopsy for both limbs and hip adductor biopsy for both limbs
Cp3	Rotation biopsy of the left leg bone
Cp4	Lengthening the Achilles tendon for both limbs and lengthening the posterior tendons of the knee joint for both limbs
Cp5	Lengthening the Achilles tendon on the right limb
Cp6	Lengthening the Achilles tendon in both limbs
Cp7	Lengthening the Achilles tendon and knee joint tendons on the right side only
Cp8	Lengthening the Achilles tendon in both limbs
Cp9	Lengthening the Achilles tendon in both limbs
Cp10	Lengthening the Achilles tendon and knee joint tendons on the right side only

4-2- Features extraction

Considering the reference studies and the methods of dealing with angles. It was found that the important angles during the gait cycle of the joints are located at the positive or negative peaks of the joint angle trajectory as shown in Figure 1.

The Important angles take the numbers 1-2-3-4.

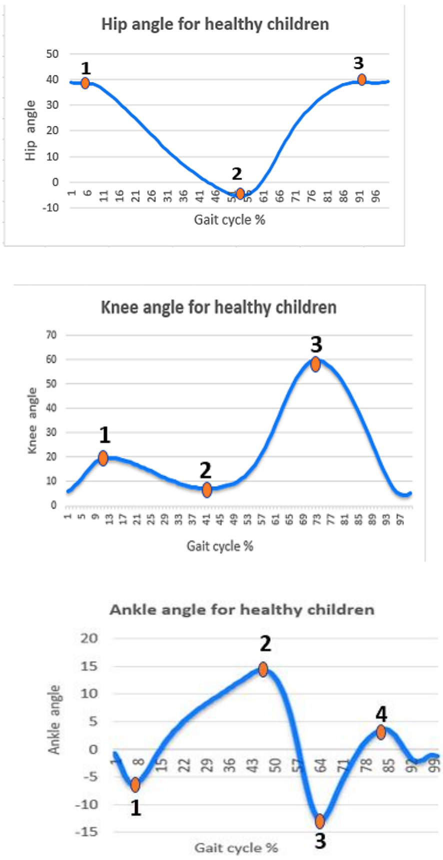

Figure 1. Points of interest from angle trajectories used as input to the fuzzy system, up hip angle trajectory, in the middle knee angle trajectory, down ankle angle trajectory (Al-Mawaldi &Khadour, 2022).

Based on the angle charts and tables found in the reference studies for healthy children, the important angles (peaks) were extracted from each study with their standard deviation, and averages were calculated in Table 4. But when talking about constructing fuzzy logic according to the values of important angles, their occurrence times as a percentage of the gait cycle must be taken into account. Therefore, the time of occurrence of the angles and their standard deviations were extracted, and the averages (for times and their standard deviations) were calculated. Table 4 shows the average angles, average times, and standard deviations for all the reference studies in Table 1 which was used in constructing the fuzzy system.

Table 4. The average angles, times, and standard deviations used in constructing the fuzzy system

Joint	Variable	1	2	3	4
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Ankle	Angle (deg)	-5.5 (±3)	14 (±4.42)	-13 (±4)	4.3 (±3)
	Time (% of the Gait cycle)	8 (±3)	46 (±3)	66 (±3)	86 (±3)
Knee	Angle (deg)	20 (±3.2)	8 (±3.5)	64 (±5.6)	-
	Time (% of the Gait cycle)	13.5 (±3)	43 the (±3)	73 (±3)	-
Hip	Angle (deg)	38 (±4)	-6 (±4.5)	39.5 (± 5)	-
	Time (% of the Gait cycle)	5 (±3)	54.5 (±3)	91 (±3)	-

4-3- Fuzzy Logic Model

Proposed fuzzy system

Figure 2 shows The block diagram of the proposed fuzzy system, whose final result will give an index for evaluating the knee and ankle deviation.

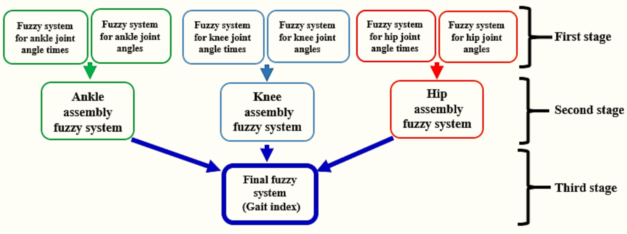

Figure 2. The block diagram of the proposed fuzzy system

The proposed system consists of three stages, as shown in Figure 2.

Subsystems in the first stage detect the deviations in gait based on the values of angles or their occurrence times (% of the gait cycle) according to the system at the level of the hip, knee and ankle joints. The output of each system at this stage is a numerical value between zero and one, where 0 means that there is no deviation in gait from the baseline (normal children), and 1 indicates the largest deviation that the subsystem can enumerate.

The three subsystems in the second stage take their inputs from the output of the fuzzy subsystems in the first stage and also give their output a digital value between zero and one.

The third stage is the (FL2-AKHDI), which gives a numerical value between zero and one. The values range according to the hip, knee and ankle deviation from zero (no deviation in gait from the baseline) to one (the largest deviation that the subsystem can enumerate).

The FLS output has the same design for all systems. It has four fuzzy sets: Normal, Medium, High, and Extremely high. These fuzzy sets describe how close gait parameters are to the normal ones (normal children). When the fuzzy output is Normal, this means that the gait is as close as possible to the normal gait, while Extremely high indicates a great deviation from the normal gait.

Type-2 fuzzy logic system (T-2 FLS)

In this study, T2-FLS was used to build all fuzzy logic systems using Matlab R2019aVR by IT2-FLS open-source toolbox (Taskin et.al., 2015)

The internal structure of T2-FLS is similar to its type-1 counterpart. However, the main differences are that T2-FLS employs and uses type-2 fuzzy sets as well as a type-reduction process (Taskin et.al., 2015) as shown in Figure 3.

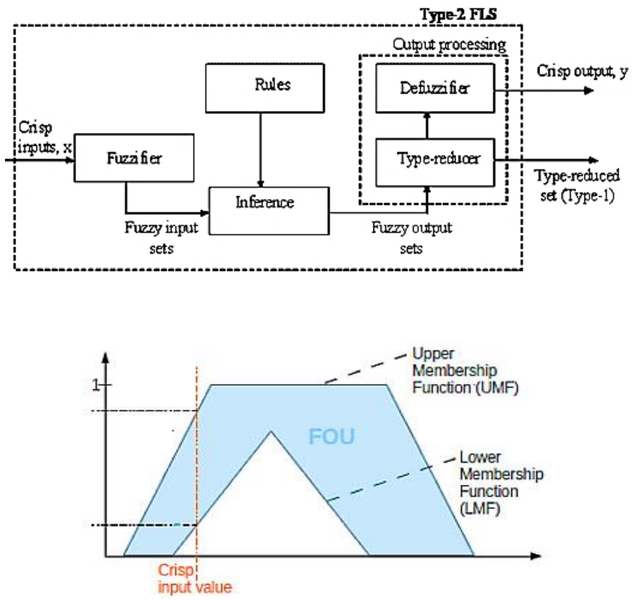

Figure 3. up: Structure of type-2 fuzzy system (Taskin et.al., 2015). down: A fuzzy set of a type-2 FLS (Sprunk et.al., 2013)

A type-2 fuzzy set consists of two type-1 fuzzy sets: One upper membership function $\overline{\mu}_{\tilde{A}}(x)$ (UMF) and a lower membership function $\underline{\mu}_{\tilde{A}}(x)$ (LMF). The area in between the two is called the footprint of uncertainty (FOU) as depicted in Figure 3. Since the output is a type-2 fuzzy set as well, it is necessary to use a type reduction before defuzzification (Taskin et.al., 2015). A type-2 fuzzy set ($\tilde{A}$) is defined by a type-2 membership function $\mu_{\tilde{A}}(x,u)$ as:

$$\tilde{A} = \{((x,u), \mu_{\tilde{A}}(x,u)) \forall_x \in X, \forall_u \in J_x \subseteq [0,1]\}$$

Where: $0 \le \mu_{\tilde{A}}(x,u) \le 1$, x and u are the primary and secondary membership variables, J_x is the primary membership function of x. The FOU of the type-2 fuzzy set is given by:

$$\text{FOU}(\tilde{A}) = \bigcup_{\forall x \in X} (\underline{\mu}_{\tilde{A}}, \overline{\mu}_{\tilde{A}}(x))$$

Type-2 FLS has the potential to deal with the high level of uncertainties presented in a system. Therefore, this study uses interval type-2 FLS, which is fully explained (Taskin et.al., 2015).

In this study, a Sugeno type-2 FL system was used to build all fuzzy logic systems. Fuzzy membership functions of type zmf, trimf, and smf were used for all fuzzy logic systems of the first stage Figure 2, where each input has three membership functions, as Figure 4 shows.

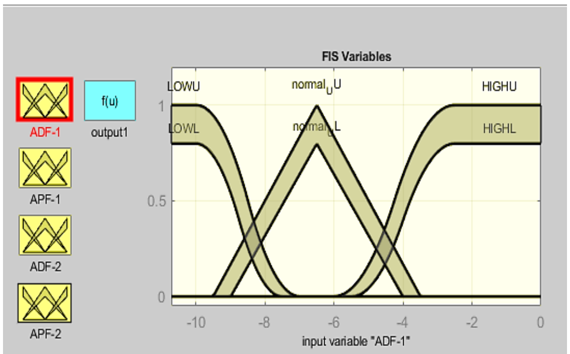

Figure 4. It shows the membership functions used for one of the fuzzy logic systems in the first stage.

while the trimf membership function was used to construct the inputs for the fuzzy logic systems in the second and third stages Figure 5.

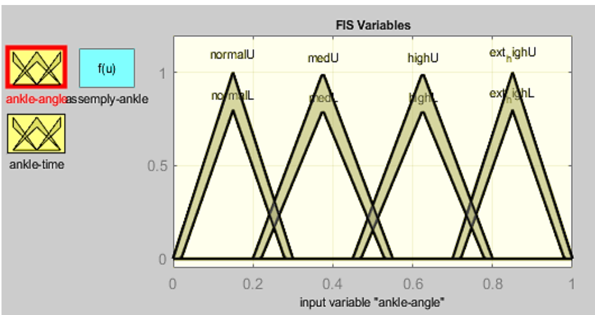

Figure 5 shows the membership functions of the inputs used for one of the fuzzy logic systems in the second and third stages.

The outputs of all fuzzy logic systems are constant crisp, and their reduction and defuzzification method is the Karnik-Mendel Algorithm (KM) (Taskin et.al., 2015). Fuzzy logic rules are designed using the Takagi-Sugeno method:

$$R_i: if\ x_1 is\ A_{i1}\ AND.,x_{ni}\ isA_{in}THEN\ y_i\ is\ a_{0i}$$

Where: x_1, is the first input, A_{i1} is the fuzzy set of the first input, i is the rule number, while y_i is the output of rule i and a_{0i} is the fuzzy set of that output (in this case, it is a constant crisp value). The number of the fuzzy logic rules is:

81 for each of the systems of ankle in the first stage.

27 for each of the systems of knee and hip in the first stage.

16 for each of the systems in the second stage.

64 for the final system in the third stage.

The method used to determine the number of rules for fuzzy systems used in this research for any fuzzy system depends on fixing the membership function for an input at a certain fuzzy value and taking all the possibilities corresponding to the other input or inputs. For example on the level of ankle joint in the first stage: the fuzzy system that deals with angle values, we have four inputs. For each input there are four membership functions, the sum of the resulting probabilities is 81 probabilities and they correspond to 81 rules.

The output of Sugeno FL is a specific numerical value so there is no need for defuzzification, and accordingly, the output field, which ranges from 0 to 1, has been divided into four parts, as shown in Figure 6. The output surface for fuzzy systems is shown in Figure 7.

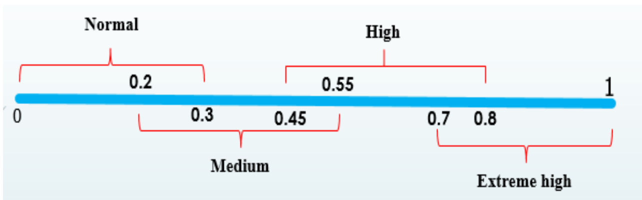

Figure 6. The output field of the fuzzy system and its division

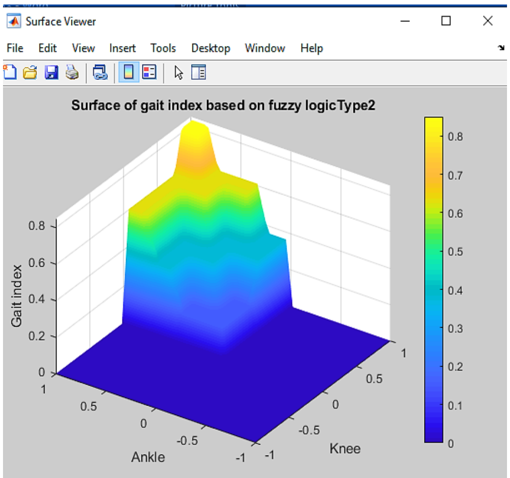

Figure 7. Shows the surface of the final fuzzy system

5- Results

The results will be discussed in three sections:

1- Results for healthy children from reference studies

By applying the angles and their occurrence times mentioned in the reference studies shown in Table 2 and following the system in Figure 2, the (FL2-AKHDI) output was obtained, which appears in Table 5 and Figure 8, which shows that all the results fall within the normal range specified in Figure 6. Except for the study (Ye ma et all .2019) falls in the middle of the medium range.

Table 5. Output of the proposed fuzzy system (Gait index) for healthy children

Researcher's name	Year of research completion	(FL2-AKDHI)
Stansfield et.al	2005	0.15
Victoria et.al	2006	0.23
Katarzyna et.al	2019	0.15
Ye ma et.al	2019	0.37
Jurgita et.al	2022	0.15

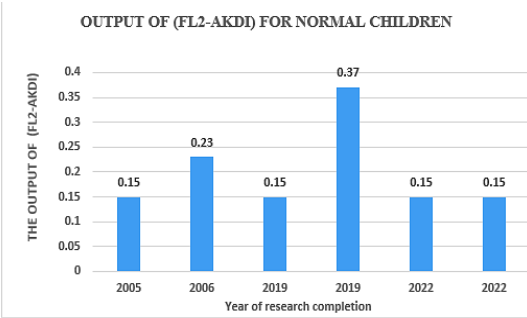

Figure 8. Output of the final fuzzy system

2- Results of the fuzzy system for healthy children from reference (Al-Mawaldi &Khadour, 2022)

When evaluating the (FL2-AKHDI) on the group of healthy children reference (Al-Mawaldi &Khadour, 2022) as Figure 9 shows the most of indicator values were located at the midpoint of the medium deviation range and below Figure 6 within the experimental and measurement errors for the kinematic data. Depending on the specificity of the case, these values will be considered normal so that children before and after surgery can later be compared together.

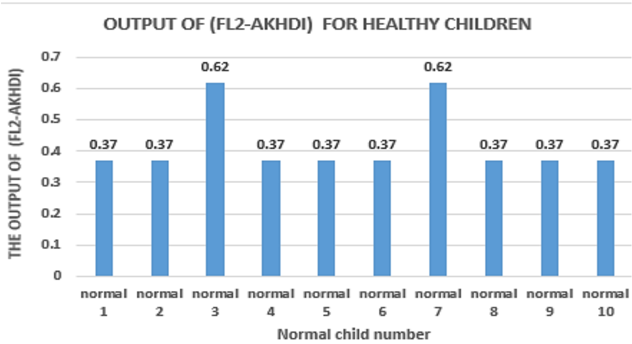

Figure 9. Output of the of the final fuzzy system for healthy children.

3- Results of the fuzzy system for children with cerebral palsy

When the (FL2-AKHDI) was applied to children with cerebral palsy before and after surgery, the results for the right limb were shown in Figure 10.

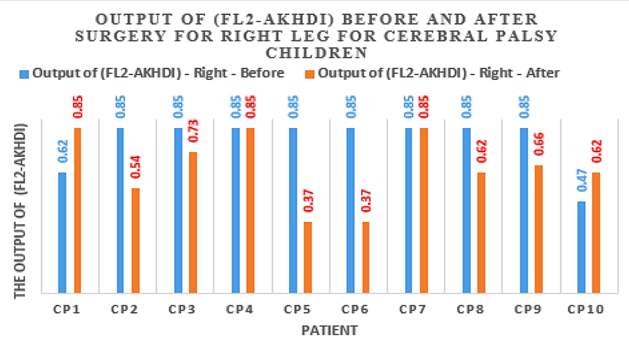

Figure 10. Output of (FL2-AKHDI) before and after surgery for the right limb for children with cerebral palsy.

For the left side, the results were as shown in Figure 11.

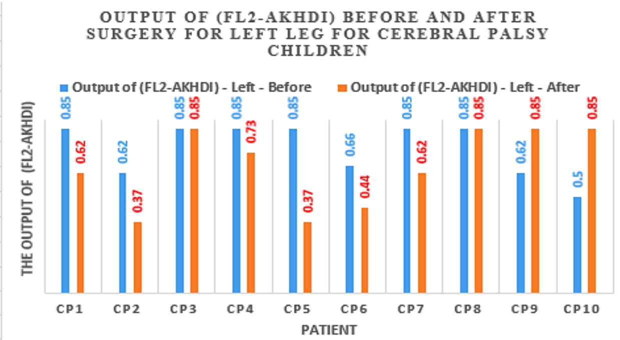

Figure 11. Output of (FL2-AKHDI) before and after surgery for the left limb for children with cerebral palsy.

To be able to make a comparison with the results of datasets 1 and 2, a special collection system was built that takes as its input the results of the (FL2-AkHDI) for the right and left limbs and gives in its final result the numerical value equivalent to the ankle-knee deviation according to the index as shown in Figure 12. In its structure, this clustering system mimics the clustering systems found in the second stage, Figure (2), in terms of the number of inputs, the nature of the membership functions used, the division of the output field, and also the number of fuzzy rules.

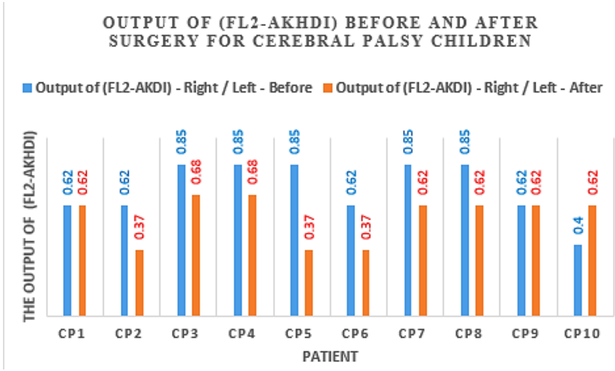

Figure 12. The output of (FL2-AKHDI) before and after surgery for both limbs together for children with cerebral palsy.

For most patients, there is a significant improvement in (FL2-AKHDI) after surgery. This improvement is evidenced by lower (FL2-AKHDI) for the majority of patients, indicating that their ability to walk has generally improved after surgery. However, there are some patients (cp2, cp5 and cp6) whose postoperative (FL2-AKHDI) are significantly lower compared to others. For some patients, the index remaining the same before and after surgery indicates that the surgery may not have been effective or that they may have suffered from complications or other factors such as poor adherence to physical therapy or weight gain that may have affected their recovery after surgery. The mean preoperative (FL2-AKHDI) (0.713) is higher than the mean postoperative (FL2-AKHDI) (0.557), indicating an overall improvement in (FL2-AKHDI) across the patient group after surgical intervention.

On the other hand,

(Baker et al. 2009) proposed a GPS index whose features can be calculated directly from data for the individual under study and average data for people without walking impairment. GPS knows the root mean square (RMS) difference between a particular gait trial and averaged data from people with no gait pathology. It has an advantage over the other indices as it is comprised of several gait variable scores (GVSs) representing an equivalent RMS difference for different kinematic variables.

Table 6 shows the mean values of the (FL2-AKHDI) and the mean of the GPS index before and after surgery for children with cerebral palsy

Table 6. Values of the proposed index and the GPS index

Index	Before surgery	After surgery
GPS (Al-Mawaldi &Khadour, 2022)	16.4	12.2
Mean of (FL2-AKHDI)	0.713	0.557

The percentage decrease in the mean index value before and after surgery for children with cerebral palsy was calculated. It was 25% for GPS while it was 21% for the (FL2-AKHDI). The close ratio reflects the accuracy of the (FL2-AKHDI) to express walking deviation in cerebral palsy children.

In the end, as an important final result of this proposed (FL2-AKHDI), we summarize in Table 7 the ranges of the values of the index for healthy children and patients before and after surgical operations.

Table 7. The areas of the indicator values according to the studied case.

Case of Interest	Range of (FL2-AKHDI) before surgery
Normal children	For most patients 0 – 0.37
Children with cerebral palsy before surgery	For most patients > 0.5
Children with cerebral palsy after surgery	0.37 - 0.85

6- Discussion

This study presents a system for evaluating hip, knee, and ankle joint deviation in the form of a digital index by extracting some important features related to the ankle knee, and hip joints and using them as input to a fuzzy system composed of several stages. These features differ in their values between healthy and cerebral palsy cases. The (FL2-AKHDI) value for most healthy children was in the middle of the range of medium deviation Figure 6. For children with cerebral palsy, it decreased in most children from the range of high deviation to medium deviation after operation.

In this part, we discuss more clarification with charts for ankle, knee, and hip joint angles before and after surgery for some patients described in dataset 3 to increase the clarification of the index performance accuracy. By comparing the results in Figure 12 with the angle diagrams from reference (Al-Mawaldi &Khadour, 2022).

The results in Figure 12 were compared with the angle diagrams in the reference study (Al-Mawaldi &Khadour, 2022). It was found that the patient (cp1) had the same index value before and after surgery, where The reason for this is the significant weight gain after surgery, which made it difficult for the muscles to stretch and bear the extra weight of the body. and this result is consistent with the angular diagrams of the hip, knee and ankle joints shown in Figure 13.

The patient (cp5) had a decrease in his index value from (0.85) to (0.37) and this falls within the middle of the range of medium deviation according to Figure 6. This is consistent with the improvement in patients' angle diagrams as shown in Figure 14.

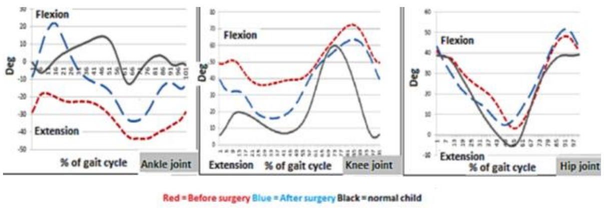

Figure 13. Angles diagrams of the ankle, knee and hip joints for the patient (Cp1) before and after surgery (Al-Mawaldi &Khadour, 2022)

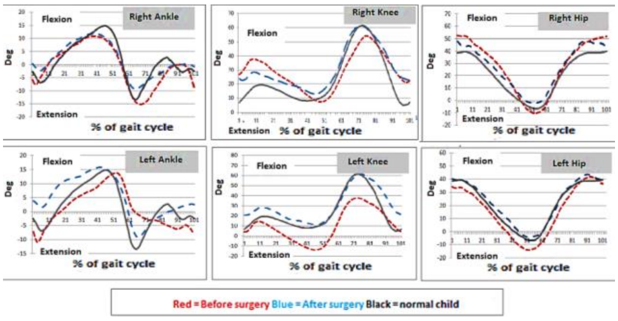

Figure 14. Angles diagrams of the ankle, knee and hip joints for the patient (Cp5) before and after surgery (Al-Mawaldi &Khadour, 2022)

While for the patient Cp7: Comparison with preoperative and postoperative angle diagrams Figure 15. There was a slight improvement at the level of the ankle joint, but the angle values remained significantly outside the normal range, while no noticeable improvement occurred at the level of the hip and knee joints, therefore the index fell slightly.

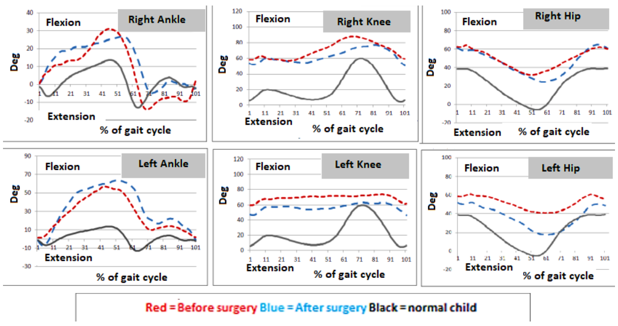

Figure 15. Angles diagrams of the ankle, knee and hip joints for the patient (Cp7) before and after surgery (Al-Mawaldi &Khadour, 2022)

For the patient Cp10: as Figure 16 shows, the patient did not experience improvement and return to the normal range or approach it, and this result is consistent with what reference (Al-Mawaldi &Khadour, 2022) indicated, and this explains the increase in the index value after surgery.

In the end, the research reached the possibility of using fuzzy logic type-2 to provide a digital indicator that gives a good visualization of the extent of deviation in gait from normal values, according to areas of deviation that were adjusted in proportion to the characteristics of the cases studied, healthy and cerebral palsy

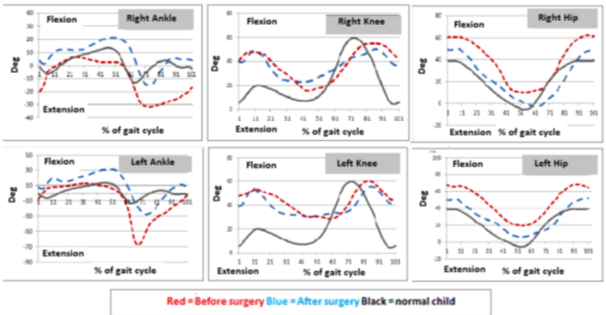

Figure 16. Angles diagrams of the ankle, knee and hip joints for the patient (Cp10) before and after surgery (Al-Mawaldi &Khadour, 2022)

7- Conclusion

In this study, a smart index (FL2-AKHDI) was designed to numerically evaluate the amount of gait deviation. The (FL2-AKHDI) was validated and was consistent with the Gait Profile Score (GPS). Its importance lies in evaluating gait deviation before and after surgery and the possibility of using it to determine the effectiveness of a specific surgical procedure at the level of a specific joint in improving gait. It is also worth its effectiveness in monitoring gait improvement during physical therapy activities and at intermittent time intervals

8- Future work

In future work, it is possible to integrate multiple fuzzy systems that take into account forces and moments with a user interface to enhance the effectiveness of using the system in medical work.

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