Gait Impairment Score: A Fuzzy Logic-Based Index for Gait Assessment

Gait Impairment Score: a fuzzy logic-based index for gait assessment

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ABSTRACT

The objective assessment of subject's gait impairment is a complicated task. For this reason, several indices have been proposed in literature for achieving this purpose, taking into account different gait parameters. All of them were essentially based on the identification of "normality ranges" for the gait parameters of interest or of a "normal population". However, it is not trivial to obtain a unique definition of "normal gait". In this study we proposed the Gait Impairment Score (GIS) that is a novel index to evaluate the subject's gait impairment level based on fuzzy logic. This index was obtained combining two Fuzzy Inference Systems (FISs), based on gait phases (GP) and knee joint kinematics (JK) parameters, respectively. Eight GP parameters and ten JK parameters were extracted from the basographic and knee kinematic signals, respectively. Those signals were acquired, for each subject's lower limb, using a set of wearable sensors connected to a commercial system for gait analysis. Each parameter was used as input variable of the corresponding FIS. The output variable of the two FISs represented the impairment level from the GP and JK point of view. GP-FIS and JK-FIS were applied separately to both right and left leg parameters. Then, the fuzzy outputs of the two FISs were aggregated, independently for each side, to obtain the leg fuzzy output. The final subject's GIS was obtained aggregating the fuzzy outputs of the two legs.

The score was validated against two gait analysis experts on a population of 12 subjects both with and without walking pathologies. The Analytic Hierarchy Process (AHP) pairwise comparisons were used to obtain the subjects' ranking from the two experts. The same population was scored using the GIS and ordered in ascending order. Comparing the three rankings (from our system and from the two human experts) it emerged that our system gives the same "judgment" of a human expert.

KEYWORDS

Analytic Hierarchy Process (AHP), foot-switch signal, Fuzzy Inference System (FIS), gait analysis, knee joint kinematics

1. INTRODUCTION

Gait analysis is used to quantitatively assess the normal and pathological function of human walking [1]. In clinics, it is employed in the care of many orthopedic and neurological disorders for surgery planning and outcome evaluation [2], to document functional changes in patient follow-up or to evaluate the effectiveness of rehabilitation protocols [3]. Two fundamental aspects of gait analysis are: 1) timing gait phases, 2) studying joint kinematics of a subject's walk.

Many spatio-temporal and joint kinematics parameters are usually computed to quantitatively assess a patient's gait. However, the presence of many parameters and the uncertainty associated to each parameter makes it difficult to objectively score a subject's walking performance, to assess treatment effectiveness comparing the same subject at different times or for comparing different subjects. This data complexity was perceived as an obstacle for the clinical use of gait analysis in many practical situations. For this reason, in recent years, there has been a growing awareness of the need for a concise index, a single measure of the "quality" of a subject's gait pattern [4].

Therefore, great efforts were devoted to build indices that summarize and condense the information arising from many parameters into a single indicator or score. As an example, the Normalcy index (NI) or Gillette Gait Index (GGI) was proposed to quantify the extent by which a patient's gait deviates from that of an impaired control group [5]. It uses principal component analysis on 16 gait parameters, and was validated on a population of children with cerebral palsy. The more recent Gait Deviation Index (GDI) is based on the extraction of 15 gait features using the singular value decomposition [6]. Similarly to the GDI, the gait profile score (GPS) [7] summarizes the overall quality of the patient's kinematics.

Moreover, almost all the methods that can be found in literature need - as a basic ingredient - the knowledge of clear normality ranges for the gait parameters of interest, to have a reference for pathological gait. Subjects with no pathologies related to gait are typically recruited and evaluated to form a control group and obtain normality ranges. However, obtaining clear, definite, crisp normality ranges is not a trivial aspect due to the wide range of gait patterns existing in healthy subjects [8, 9]. In general, it is not easy to define a single common gait pattern that can be defined as "normal".

Fuzzy Inference System (FIS) is a method based on fuzzy logic suitable for constructing an index without the need to define crisp ranges for the involved parameters/variables [10]. It is a way of mapping several input variables into one or more output variables, managing the uncertainty related to variable ranges that do not present sharp borders [11]. This is possible by using Membership Functions (MFs). A MF returns a value in the range of [0,1], representing the membership degree of an element to a set (0 = it doesn't belong to the set, 1 it completely belongs to the set). Moreover, a FIS tries to formalize the reasoning process of human language building fuzzy IF-THEN rules that connect input and output variables.

In order to overcome problems related to the uncertainty inherent to the concept of "normal gait", a previous work built a FIS to obtain a basographic gait impairment score [12]. That FIS was based only on parameters obtained from gait phases, thus neglecting the information arising from joint kinematics.

In general, a fundamental problem encountered when presenting a new index or score is to validate it. Typically, the score is compared to the results obtained by scales and questionnaires already validated, considered as gold standard. However, if the comparison has to be performed against one or more experts, it is necessary to ask them to assign a value to each element or to sort elements in ascending or descending order according to some criteria.

Analytic Hierarchy Process (AHP) [13] is a technique commonly employed for complex decision making that allows for automatically ranking several elements on the base of user judgments. It provides a complete framework for structuring problems in hierarchical manner, defining and weighting evaluation criteria, and comparing alternative solutions.

AHP is based on three main steps. Firstly, the evaluation criteria have to be selected and hierarchically organized. In the second step the pairwise comparison of all elements is performed for each criterion. Finally, all alternatives are automatically ranked based on the expressed judgments. The main advantage of this kind of approach lies in the pairwise comparison of alternatives. In fact, for an expert or a decision maker it is easier to compare two elements between them than to sort several items in ascending or descending order.

The aim of this work is to present a novel index to evaluate the subject's gait impairment level. The index is the result of the aggregation of two FISs: one based on gait phases (GP) parameters and the second one based on knee joint kinematics (JK) parameters. The score was validated against two experts of gait analysis using AHP pairwise comparisons.

2. Materials and Methods

2.1 Populations

Two populations of subjects were used in this study: one for the FIS construction (training set) and one for its validation (test set).

For constructing the MFs and defining the fuzzy rules we used the gait signals recorded on a population of 30 subjects (age 34 ± 17 years) with no neurological or orthopedic pathologies that could influence their gait.

For the FIS validation we used a different population made of 12 subjects divided as follows: 5 healthy subjects (age 41 ± 26 years), 5 subjects with hip prosthesis (age 71 ± 6 years) and 2 subjects suffering of normal pressure hydrocephalus (79 and 80 years old respectively).

The experimental protocol conformed to the ethical principles of the Helsinki declaration.

2.2 Signal acquisition and processing

The subject was asked to walk at self-selected speed for 2-3 minutes, to collect at least 100 gait cycles. The multichannel system STEP32 (Medical Technology, Italy) was used to acquire gait signals, for each lower limb (sampling frequency: 2 kHz) [14][15].

Foot-switches (size: 10 mm × 10 mm × 0.5 mm; activation force: 3 N) were placed under the barefoot soles (beneath the heel, 1st and 5th metatarsal heads) to acquire the “basographic signal” or “gait phase’s signal” (see Fig.1, first row). This allows for timing gait events. The basographic signal was then debounced, converted to 4 levels (Heel contact (H), Flat foot contact (F), Push-off (P), Swing (S)), and processed to segment gait cycles [16].

Electrogoniometers were attached to the lateral side of each lower limb to record knee joint kinematics in the sagittal plane (see Fig.1, second row). The knee kinematic signal was low-pass filtered (FIR filter, 100 taps, cut-off frequency of 15 Hz) and segmented into separate gait cycles.

2.3 Gait parameter extraction

In healthy subjects, the most common gait cycle consists of the sequence of H, F, P, S gait phases. In pathological subjects a higher percentage of “atypical cycles” may be observed, that do not follow this sequence [16]. Among atypical cycles there are cycles that initiate with a forefoot contact instead of a heel contact (forefoot cycles) [17]. Furthermore, in pathological subjects, even cycles presenting a normal sequence HFPS may show altered phase duration: H, F, P and S may be augmented or shortened with respect

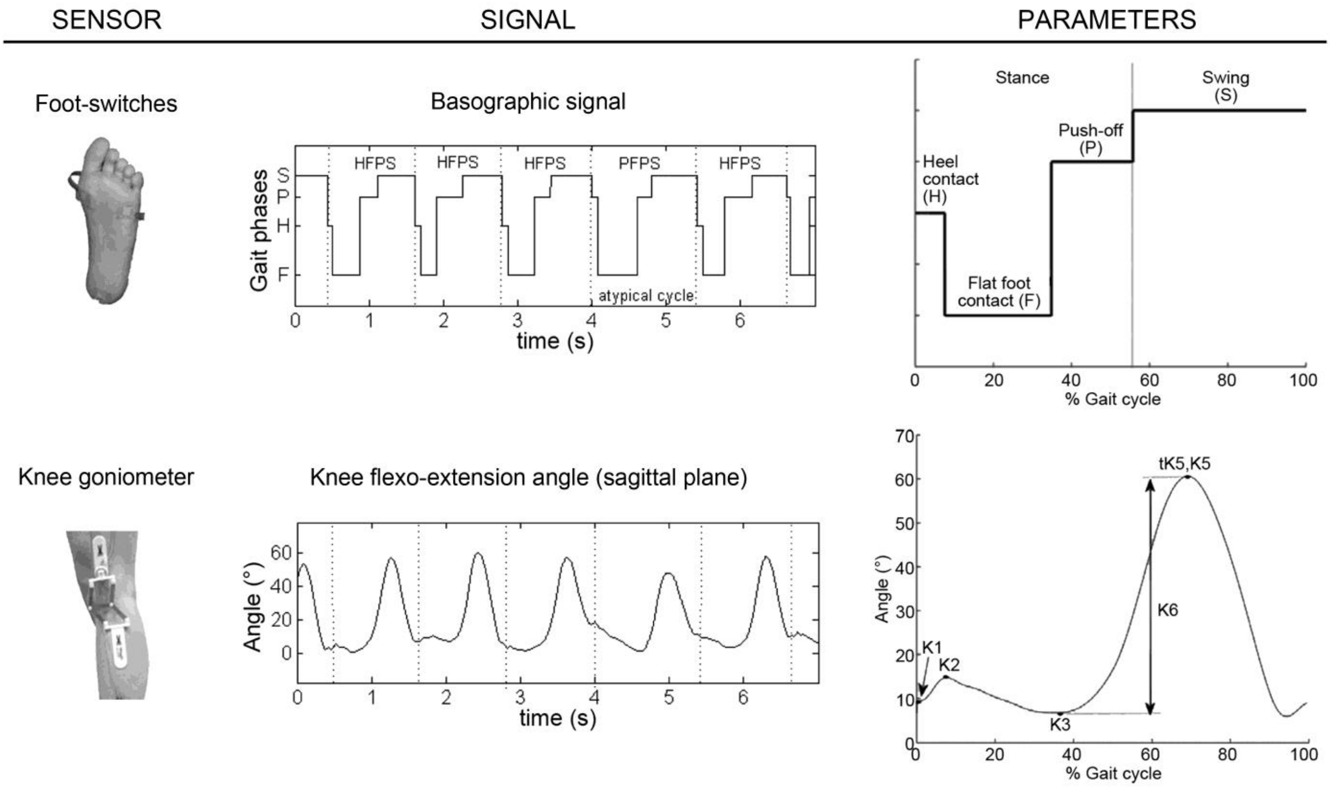


Fig. 1. Foot-switches placed under the sole allow for timing gait events. Segmenting the gait phase's signal, the average duration of the gait phases (H, F, P and S) is obtained. A knee goniometer (articulated parallelogram) allows for recording the knee joint kinematics during gait. From the average kinematic curve, typical parameters are extracted (K1, K2, etc…).

to the corresponding phases observed in "normal" gait.

On the base of these considerations and of spatio-temporal parameters usually adopted in clinics, we extracted the following 8 GP parameters: duration of H, F, P, S gait phases, cadence [1], double support, atypical and forefoot cycles, as listed in Table I. "Double support" is the period during which both feet are in contact with the ground (expressed as a percentage of the gait cycle, GC). "Atypical cycles" is the percentage of cycles that do not follow the standard sequence of gait phases (HFPS). "Forefoot cycles" is the percentage of atypical cycles beginning with a forefoot strike. For each subject, all GP parameters, except atypical and forefoot cycles, were estimated as means across HFPS cycles.

The knee flexo-extention angle during gait is by far the most studied kinematic curve in clinical gait analysis. It is customary to extract parameters from the knee joint curve to obtain relevant clinical information, such as the knee flexion at heel strike (K1), maximum flexion at loading response (K2), maximum extension in stance (K3), maximum flexion in swing (K5), and total sagittal range of motion (K6) [12].

A total of 10 JK parameters were extracted from the knee flexo-extention curves corresponding to HFPS cycles, as listed in Table I. In particular, for each subject, 8 parameters were extracted from the mean kinematic curve: K1, K2, K3, K5, K6, the difference between K2 and K1, the difference between K2 and K3 (all expressed in degrees), time of flexion peak (tK5 expressed as % GC). Two additional parameters were calculated considering all the kinematic curves of a subject: the standard deviation in correspondence of K1 and K5 (in degrees).

2.4 GP-FIS and JK-FIS description

The Gait Impairment Score is the result of a system that combines two FISs: GP-FIS, based on GP parameters (extracted from the basographic signal) and JK-FIS, based on JK parameters (extracted from the knee flexo-extention curve). Each FIS returns a score of the impairment related to the corresponding signal, separately for each leg. The two FIS outputs are then combined to obtain a leg-score and, finally, right- and left-leg outputs are combined to obtain the final Gait Impairment Score.

The Mamdani method was chosen as inference technique for both FISs. It consists of four steps: *fuzzyfication* for transforming crisp inputs into fuzzy representations, *rule evaluation* in which input and output variables are connected, *aggregation* of all rules to obtain the final fuzzy set, and finally *defuzzification* in which a crisp number is obtained as output.

The Fuzzy Logic toolbox provided in Matlab® environment was used for the FISs implementation.

2.4.1 FIS Variables

We constructed an input variable for each extracted gait parameter, for a total of 8 variables for the GP-FIS and 10 variables for the JK-FIS. The ranges for each variable were determined according to the parameter they represent, and they are listed in the third column of Table I.

All input variables were modelled using trapezoidal MFs associated to different levels of alteration of the corresponding parameter. The list of the MFs associated to each input variable is reported in the last column of Table I, for GP-FIS and JK-FIS.

For the construction of the trapezoidal MFs related to the no altered condition, we analyzed the distribution of values calculated from the training set. More specifically, for each variable we used the maximum and minimum values obtained from the population as limits of the longer trapezoid base, and the 25th and 75th percentiles as range of the shorter trapezoid base. The values used for the construction of the MF associated to the no altered condition are shown in Table II for both GP and JK input variables.

The MFs corresponding to altered conditions were defined as the fuzzy standard complement of the normal conditions. As an example, the 3 MFs constructed for the input variable “F-phase” (“decreased”, “normal” and “increased”) are showed in Fig. 2.

For both GP-FIS and JK-FIS, we defined a unique output variable, representing the impairment level and ranging from 0 to 1. Four levels of gait impairment (“no impairment”, “mild impairment”, “moderate impairment”, “severe impairment”) were associated to the output, each modelled by a triangular MF. The output variable is showed in Fig. 3.

TABLE I
LIST OF MEMBERSHIP FUNCTIONS (MFS) FOR EACH INPUT VARIABLE

FIS	Input Variable	Variable Range	MFs
Gait Phase Parameters	H-phase (% GC)	0 ÷ 100	Decreased, Normal, Increased
	F-phase (% GC)	0 ÷ 100	Decreased, Normal, Increased
	P-phase (% GC)	0 ÷ 100	Decreased, Normal, Slightly Increased, Increased, Highly Increased
	S-phase (% GC)	0 ÷ 100	Decreased, Normal, Increased
	Cadence (cycles/min)	0 ÷ 100	Decreased, Normal, Increased
	Double Support (% GC)	0 ÷ 100	Normal, Increased
	Atypical Cycles (%)	0 ÷ 100	Few, Medium, Many
	Forefoot Cycles (% atypical)	0 ÷ 100	Few, Many
Joint Kinematic Parameters	K1 (°)	0 ÷ 90	Decreased, Normal, Increased, Highly Increased
	K2 (°)	0 ÷ 90	Decreased, Normal, Increased
	K3 (°)	0 ÷ 90	Decreased, Normal, Increased
	K5 (°)	0 ÷ 90	Highly Decreased, Decreased, Slightly Decreased, Normal
	K6 (°)	0 ÷ 90	Highly Decreased, Decreased, Slightly Decreased, Normal
	K2-K1 (°)	-100 ÷ 100	Negative, Positive
	K2-K3 (°)	-100 ÷ 100	Negative, Positive
	tK5 (% GC)	0 ÷ 20	Decreased, Normal, Increased
	σK1 (°)	0 ÷ 20	Normal, Increased, Highly Increased
	σK5 (°)	0 ÷ 100	Normal, Increased, Highly Increased

TABLE II

POINTS DEFINING THE TRAPEZOIDAL MF OF THE NO ALTERED CONDITIONS FOR EACH INPUT VARIABLE

	Input Variable	A	B	C	D
Gait Phase Parameters	H-phase (% GC)	3	4	7	12
	F-phase (% GC)	14	28	34	41
	P-phase (% GC)	13	19	24	33
	S-phase (% GC)	36	40	44	49
	Cadence (cycles/min)	43	50	59	63
	Double Support (% GC)	0	0	19	25
	Atypical Cycles (%)	6	13	18	39
	Forefoot Cycles (% atypical)	0	0	40	50
Joint Kinematic Parameters	K1 (°)	0	5	15	25
	K2 (°)	4	12	20	32
	K3 (°)	-7	0	7	16
	K5 (°)	39	51	90	90
	K6 (°)	40	50	90	90
	K2-K1 (°)	0	1	100	100
	K2-K3 (°)	0	5	100	100
	tK5 (% GC)	64	67	71	75
	σK1 (°)	0	0	1.7	2.8
	σK5 (°)	0	0	1.8	3.3

A and D are the limits of the lower base of the trapezoidal no altered MFs (points with membership degree equal to 0) while B and C are the limits of the upper base of the trapezoidal no altered MFs (points for which MFs assume membership degree equal to one).

2.4.2 FIS Rules

A set of fuzzy rules was defined to connect input and output variables, for each FIS. A fuzzy rule is a linguistic rule linking a set of antecedents with some consequents, in the general form of: *if x is A (antecedent) then y is B (consequent),* where x and y are variables and A and B are fuzzy sets represented by MFs. In fuzzy logic, if the antecedent is true with a certain degree of membership, then the consequent is also true with the same degree.

Rules were based on the knowledge of a gait analysis expert and information retrieved from the training dataset. A total of 72 and 36 fuzzy rules were defined for the GP-FIS and KJ-FIS, respectively.

All rules employed the "AND" fuzzy operator to connect the input sets, implemented using the "MIN" function. Appling the AND operator to fuzzy rules means that the MF defined in the rule consequent is activated with a membership degree equal to the minimum membership degree among all MFs included in the antecedent.

In order to aggregate the rules to obtain the final fuzzy set, the "OR" fuzzy operator was used, implemented using the "MAX" function.

2.4.3 Defuzzification method

The last step of the inference process was the defuzzification, applied to the output fuzzy set of both FISs in order to obtain a score.

In particular, we implemented a custom defuzzification function defined by the equation (1):

$$score = \frac{\sum_{i=1}^{4} g_i(x_{1i}+x_{2i})/2}{\sum_{i=1}^{4} g_i} \quad (1)$$

where g_i is the degree of activation of the i-th MF of theoutput variable and x_{1i} and x_{2i} are the x-axis

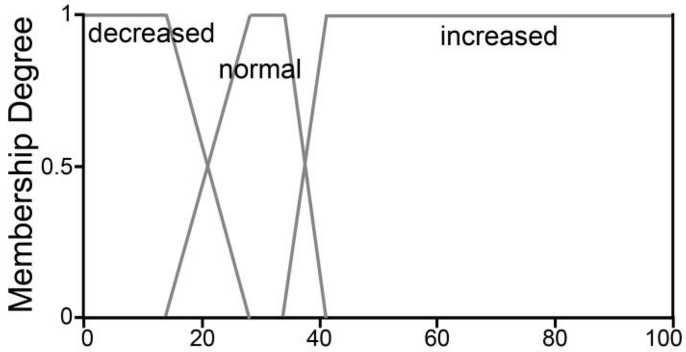


Fig. 2. GP-FIS: input variable "F-phase" (3 MFs). The "normal" MF is obtained from the values of the training set. The "decreased" and "increased" MFs are calculated as standard fuzzy complement of the "normal" MF.

projections of the *i*-th MF at degree g_i. An example of defuzzification is shown in Fig. 3.

In the case that only one output MF is activated, this defuzzification function allows for obtaining, as crisp output, the position of the MF vertex. This is particularly important for the first or the last output triangle. As an example, if only the *no impairment* MF is activated (no matter the degree of activation g1) the crisp output is equal to 0. This condition is not achievable with the most commonly used defuzzification methods, such as centroid, or middle of maximum. In all the other cases in which more than one MF is activated, the defuzzified value is a mean of the x-axis projections of the fuzzy set, weighted for their activation degrees. In this way, the obtained score can range from 0 (no impairment) to 1 (maximum level of gait impairment).

2.4.4 Gait Impairment Score calculation

GP-FIS and JK-FIS were applied twice in order to classify both right and left leg.

The fuzzy outputs of the two FISs were then aggregated, independently for each side, to obtain the leg fuzzy output. Finally, the overall fuzzy output was obtained aggregating the fuzzy outputs of the two legs. All aggregations were performed by the OR operator (implemented as MAX function).

However, defuzzification can be applied to each single step of the above described process. This allows for obtaining an impairment score related to the gait phases and another one for the kinematics aspects, for each leg. Then, the leg-score can be obtained for the right and left leg separately and, finally, the total Gait Impairment Score can be calculated to take into account both legs.

The aggregation of the fuzzy outputs and the defuzzification process is depicted in Fig. 4.

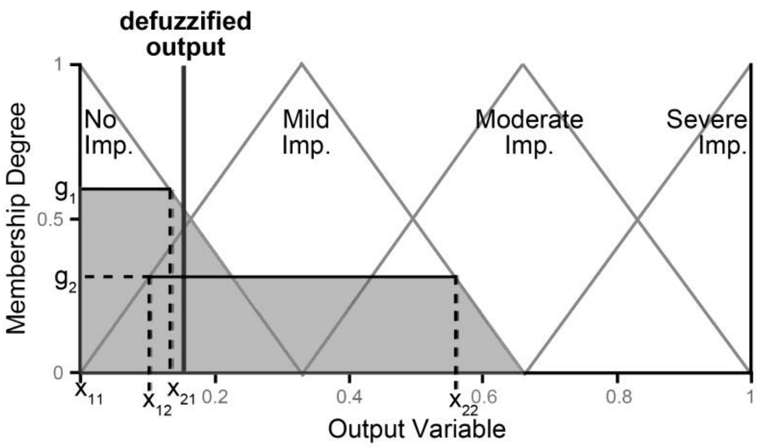


Fig. 3. Example of defuzzification of the output MFs. Grey regions highlight MF degree of activation (gi) and the vertical marked line represents the defuzzified output.

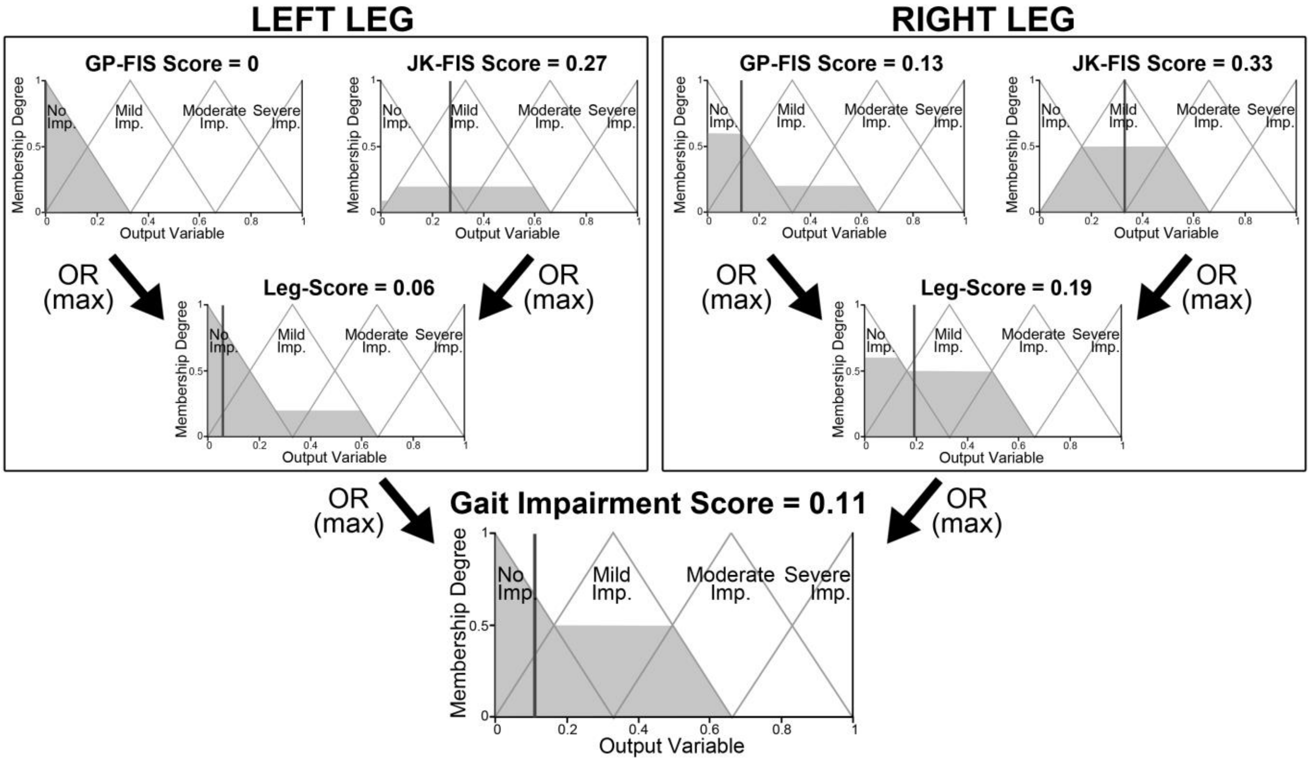


Fig. 4. Example of output aggregation using the OR operator (implemented as MAX function). First, the gait phases (GP) and joint kinematics (JK) outputs are aggregated, separately for each side, to obtain the fuzzy output of each leg. Then, the outputs of the two legs are aggregated to construct the overall gait impairment output. At each step, the vertical line represents the defuzzified output.

2.4.5 System validation by AHP pairwise comparisons

The proposed system for the objective assessment of gait impairment was validated against two gait analysis experts.

The system validation was performed in two steps. Firstly, the validation population was ordered on the base of three rankings: the judgments expressed by the two experts and the Gait Impairment Score. Then, the three rankings were compared in order to quantify their similarity.

For the first step, AHP was implemented using Priority Estimation Tool (PriEsT [18], http://sajidsiraj.com/priest/). The two experts were asked to independently evaluate the 12 subjects included in the validation group, pairwise, using a 4-point scale: equal, slightly better, better and strongly better. Expert judgments were based only on one criterion: the comparison of the global gait performance, assessed by means of the basographic and knee kinematics signals. AHP returns the subjects ranking for each expert. All subjects were also evaluated using the Gait Impairment Score and sorted according to the obtained values.

For the comparison of the 3 rankings we used the *Kendall's Tau coefficient* (τ). It measures the similarity between two orderings of n elements as:

$$\tau = \frac{n_c - n_d}{n(n-1)/2}$$

where n_c is the number of concordant (ordered in the same way) pairs and n_d is the number of discordant (ordered differently) pairs. This coefficient can range from -1, if the two rankings are completely reverse, to 1 when the two orders are exactly the same. A coefficient close to 0 represents a situation in which the two rankings are independent.

3. Results of the system validation

The results of the model validation on the test set are showed in Table III. In the first column the 12 subjects were ordered considering the output of the GIS system (ascending values of score), the last two columns report the rankings obtained through the pairwise comparisons performed by the two experts independently. From Table III it emerged that the ordering of the human experts are slightly different from the GIS one, with 3 subjects and 5 subjects in the same position between the GIS and expert 1 and 2 respectively. However, also comparing the ranking of the two experts between them, only 5 subjects can be found in the same position.

TABLE III
RANKINGS OBTAINED FROM GIS, EXPERT1 AND EXPERT2

GIS	Expert1	Expert2
S1	S2	S3
S2	S3	S2
S3	S1	S1
S4	S6	S5
S5	S4	S4
S6	S5	S8
S7	S8	S6
S8	S9	S7
S9	S7	S9
S10	S10	S10
S11	S11	S11
S12	S12	S12

The *Kendall's Tau coefficient* was calculated among the three orderings and the values are reported in Table IV.

TABLE IV
KENDALL'S TAU COEFFICIENT

	Expert1	Expert2
GIS	0.82	0.82
Expert 1	-	0.82

As it emerged from Table IV, the value of the Kendall's Tau coefficient obtained comparing GIS vs. Expert1 rankings and GIS vs. Expert2 rankings is the same obtained comparing the two experts' rankings between them. This means that the proposed GIS allows for ordering the subjects similarly to a human expert.

4. Discussion

In this work we presented a novel index that allows for an objective evaluation of the subject's gait impairment level. The index is the output of a system made of the two FISs: one based on gait phases parameters and the other based on knee joint kinematics parameters.

The results were validated against two experts of gait analysis using AHP pairwise comparisons. The validation results showed that the system behavior in terms of subjects' ordering is equivalent to the ranking obtained by two experts.

Comparing our score with the majority of the other indices proposed in literature, such as the GGI [5], the GDI [6] or the GPS [7], one main difference can be found: the other methods are essentially based on the calculation of a distance between the new subject to be scored and the average of a population of control subjects. This implies that, in those cases in which the reference population is not large enough, its mean values are strongly affected by the variation, addition or removal, of one or more subjects within it, above all in the presence of extreme elements (outliers) [19]. Consequently, also the resultant index may vary with the change of the control dataset, as it was demonstrated for the GGI [20].

The proposed system is not based on the distance between a patient and a control group, but it applies an inference procedure. More specifically, in our system only the construction of the not altered input MFs was based on the percentiles calculated across the population, that are more stable if one or more subjects are changed in the dataset. Then, a set of rules was applied to obtain the score instead of using a simple distance. Moreover, the use of a combination of FISs for the index construction allows the users for an easier and prompter understanding of the most critical aspects for a specific subject. In fact, once a final GIS value was obtained, it is possible to proceed backward analyzing the single leg scores and the GP and JK scores for each side. Furthermore, each single FIS allows for a more detailed analysis of the rules activated for a specific input, giving evidence of the motivations of a specific score value. Using indices base on mathematical transformation of the original input variables, such as the principal component analysis for the GGI [5], and the singular value decomposition for the GDI [6] and GPS [7], this analysis is more complicated and less immediate. This means that, obtained a specific score for a subject, it is difficult for the user to understand which aspect or variable mostly contributed to the final result.

Finally, our index takes into account both gait phases and joint kinematics parameters. In particular, although the importance of the basographic signal from the clinical point of view was extensively proved [15, 16, 21], no index proposed in literature considers the gait phases parameters for the score calculation.

5. Conclusions

In this work the Gait Impairment Score (GIS) was proposed for the objective assessment of the gait impairment level of a subject. This index was obtained combining gait phases parameters and joint kinematics aspects using two Fuzzy Inference Systems (FISs).

The score was validated against two gait analysis experts on a population of subjects both with and without walking pathologies. The results showed that our system “judgment” (ranking) is comparable to that of a human expert.

The use of the fuzzy logic for the system construction allows for overcoming problems related to the uncertainty inherent to the definition of a “normal gait” or a “normal population”.

Moreover, from the user point of view, the combination of two FISs facilitates the identification of the most critical aspects or limb for each specific subject.

REFERENCES

1 Perry J, 1992, "Gait Analysis: Normal and Pathological Function," SLACK Incorporated, Thorofare, New Jersey.

2 Wren T a L, Gorton GE, Ounpuu S, Tucker C a, 2011, "Efficacy of clinical gait analysis: A systematic review.," Gait Posture, 34(2), pp: 149–153.

3 Agostini V, Ganio D, Facchin K, Cane L, Moreira Carneiro S, Knaflitz M, 2014, "Gait parameters and muscle activation patterns at 3, 6 and 12 months after total hip arthroplasty.," J. Arthroplasty, 29(6), pp: 1265–72. Elsevier.

4 Cimolin V, Galli M, 2014, "Summary measures for clinical gait analysis: a literature review.," Gait Posture, 39, pp: 1005–10.

5 Schutte LM, Narayanan U, Stout JL, Selber P, Gage JR, Schwartz MH, 2000, "An index for quantifying deviations from normal gait," Gait Posture, 11, pp: 25–31.

6 Schwartz MH, Rozumalski A, 2008, "The gait deviation index: A new comprehensive index of gait pathology," Gait Posture, 28(3), pp: 351–357.

7 Baker R, McGinley JL, Schwartz MH, Beynon S, Rozumalski A, Graham HK, et al., 2009, "The Gait Profile Score and Movement Analysis Profile," Gait Posture, 30, pp: 265–269.

8 Rosati S, Agostini V, Knaflitz M, Balestra G, 2017, "Muscle activation patterns during gait: A hierarchical clustering analysis," Biomed. Signal Process. Control, 31, pp: 463–469.

9 Di Nardo F, Agostini V, Knaflitz M, Mengarelli A, Maranesi E, Burattini L, et al., 2015, "The occurrence frequency: A suitable parameter for the evaluation of the myoelectric activity during walking," In *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, IEEE. pp.6070–6073. Retrieved June 1, 2017, from http://www.ncbi.nlm.nih.gov/pubmed/26737676

10 Negnevitsky M, 2005, "Artificial intelligence : a guide to intelligent systems," Addison-Wesley.

11 Rosati S, Montanaro A, Tralli A, Balestra G, 2013, "Fuzzy logic applied to a Patient Classification

System," In *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS,* Osaka. pp.1310–1313.

12 Rosati S, Agostini V, Balestra G, Knaflitz M, 2014, "Basographic gait impairment score: A fuzzy classifier based on foot-floor contact parameters," In *2014 IEEE International Symposium on Medical Measurements and Applications (MeMeA),* pp.1–5.

13 Ishizaka A, Labib A, 2011, "Review of the main developments in the analytic hierarchy process," Expert Syst. Appl., 38(11), pp: 14336–14345.

14 Agostini V, Lo Fermo F, Massazza G, Knaflitz M, 2015, "Does texting while walking really affect gait in young adults?," J. Neuroeng. Rehabil., 12(1), pp: 86.

15 Agostini V, Lanotte M, Carlone M, Campagnoli M, Azzolin I, Scarafia R, et al., 2015, "Instrumented gait analysis for an objective pre/post assessment of tap test in normal pressure hydrocephalus," Arch. Phys. Med. Rehabil. Elsevier.

16 Agostini V, Balestra G, Knaflitz M, 2014, "Segmentation and classification of gait cycles," IEEE Trans. Neural Syst. Rehabil. Eng., 22(5), pp: 946–952.

17 Agostini V, Nascimbeni A, Gaffuri A, Knaflitz M, 2015, "Multiple gait patterns within the same Winters class in children with hemiplegic cerebral palsy," Clin. Biomech., 30(9), pp: 908–914.

18 Siraj S, Mikhailov L, Keane JA, 2015, "PriEsT: an interactive decision support tool to estimate priorities from pairwise comparison judgments," Int. Trans. Oper. Res., 22(2), pp: 217–235.

19 Rosner B (Bernard A., 2011, "Fundamentals of biostatistics," Brooks/Cole, Cengage Learning. Retrieved May 31, 2017, from https://books.google.it/books?id=-CQtWiJJL0cC&pg=PR14&lpg=PR14&dq=Fundamentals+of+Biostatistics+sixth+edition,+Bernard+Rosner&source=bl&ots=W2L5re_wfs&sig=B6oIni73QhjDRdvlqE_3do6hQ0w&hl=it&sa=X&ved=0ahUKEwjPm-GXqJrUAhVCuhQKHVoWAb0Q6AEIRDAE#v=onepage&q=Fundamentals of Biostatistics sixth edition%2C Bernard Rosner&f=false

20 McMulkin ML, MacWilliams BA, 2008, "Intersite variations of the Gillette Gait Index," Gait

Posture, 28(3), pp: 483–487. Retrieved May 31, 2017, from http://www.ncbi.nlm.nih.gov/pubmed/18439828

21 Agostini V, Knaflitz M, Nascimberi a., Gaffuri a., 2014, "Gait measurements in hemiplegic children: An automatic analysis of foot-floor contact sequences and electromyographic patterns," In *2014 IEEE International Symposium on Medical Measurements and Applications (MeMeA)*, pp.1–4.

TABLES

TABLE I: List of Membership Functions (MFs) for each Input Variable

FIS	Input Variable	Variable Range	MFs
Gait Phase Parameters	H-phase (% GC)	0 ÷ 100	Decreased, Normal, Increased
	F-phase (% GC)	0 ÷ 100	Decreased, Normal, Increased
	P-phase (% GC)	0 ÷ 100	Decreased, Normal, Slightly Increased, Increased, Highly Increased
	S-phase (% GC)	0 ÷ 100	Decreased, Normal, Increased
	Cadence (cycles/min)	0 ÷ 100	Decreased, Normal, Increased
	Double Support (% GC)	0 ÷ 100	Normal, Increased
	Atypical Cycles (%)	0 ÷ 100	Few, Medium, Many
	Forefoot Cycles (% atypical)	0 ÷ 100	Few, Many
Joint Kinematic Parameters	K1 (°)	0 ÷ 90	Decreased, Normal, Increased, Highly Increased
	K2 (°)	0 ÷ 90	Decreased, Normal, Increased
	K3 (°)	0 ÷ 90	Decreased, Normal, Increased
	K5 (°)	0 ÷ 90	Highly Decreased, Decreased, Slightly Decreased, Normal
	K6 (°)	0 ÷ 90	Highly Decreased, Decreased, Slightly Decreased, Normal
	K2-K1 (°)	-100 ÷ 100	Negative, Positive
	K2-K3 (°)	-100 ÷ 100	Negative, Positive
	tK5 (% GC)	0 ÷ 20	Decreased, Normal, Increased
	σK1 (°)	0 ÷ 20	Normal, Increased, Highly Increased
	σK5 (°)	0 ÷ 100	Normal, Increased, Highly Increased

TABLE II: Points defining the Trapezoidal MF of the No Altered Conditions for each Input Variable

	Input Variable	A	B	C	D
Gait Phase Parameters	H-phase (% GC)	3	4	7	12
	F-phase (% GC)	14	28	34	41
	P-phase (% GC)	13	19	24	33
	S-phase (% GC)	36	40	44	49
	Cadence (cycles/min)	43	50	59	63
	Double Support (% GC)	0	0	19	25
	Atypical Cycles (%)	6	13	18	39
	Forefoot Cycles (% atypical)	0	0	40	50
Joint Kinematic Parameters	K1 (°)	0	5	15	25
	K2 (°)	4	12	20	32
	K3 (°)	-7	0	7	16
	K5 (°)	39	51	90	90
	K6 (°)	40	50	90	90
	K2-K1 (°)	0	1	100	100
	K2-K3 (°)	0	5	100	100
	tK5 (% GC)	64	67	71	75
	σK1 (°)	0	0	1.7	2.8
	σK5 (°)	0	0	1.8	3.3

A and D are the limits of the lower base of the trapezoidal no altered MFs (points with membership degree equal to 0) while B and C are the limits of the upper base of the trapezoidal no altered MFs (points for which MFs assume membership degree equal to one).

TABLE III: Rankings obtained from GIS, Expert1 and Expert2

GIS	Expert1	Expert2
S1	S2	S3
S2	S3	S2
S3	S1	S1
S4	S6	S5
S5	S4	S4
S6	S5	S8
S7	S8	S6
S8	S9	S7
S9	S7	S9
S10	S10	S10
S11	S11	S11
S12	S12	S12

TABLE IV: Kendall's Tau Coefficient

	Expert1	Expert2
GIS	0.82	0.82
Expert 1	-	0.82

FIGURE CAPTIONS

Fig. 1: Foot-switches placed under the sole allow for timing gait events. Segmenting the gait phase's signal, the average duration of the gait phases (H, F, P and S) is obtained. A knee goniometer (articulated parallelogram) allows for recording the knee joint kinematics during gait. From the average kinematic curve, typical parameters are extracted (K1, K2, etc…).

Fig. 2: GP-FIS: input variable "F-phase" (3 MFs). The "normal" MF is obtained from the values of the training set. The "decreased" and "increased" MFs are calculated as standard fuzzy complement of the "normal" MF.

Fig. 3: Example of defuzzification of the output MFs. Grey regions highlight MF degree of activation (gi) and the vertical marked line represents the defuzzified output.

Fig. 4: Example of output aggregation using the OR operator (implemented as MAX function). First, the gait phases (GP) and joint kinematics (JK) outputs are aggregated, separately for each side, to obtain the fuzzy output of each leg. Then, the outputs of the two legs are aggregated to construct the overall gait impairment output. At each step, the vertical line represents the defuzzified output.

FIGURES

FIGURE 1

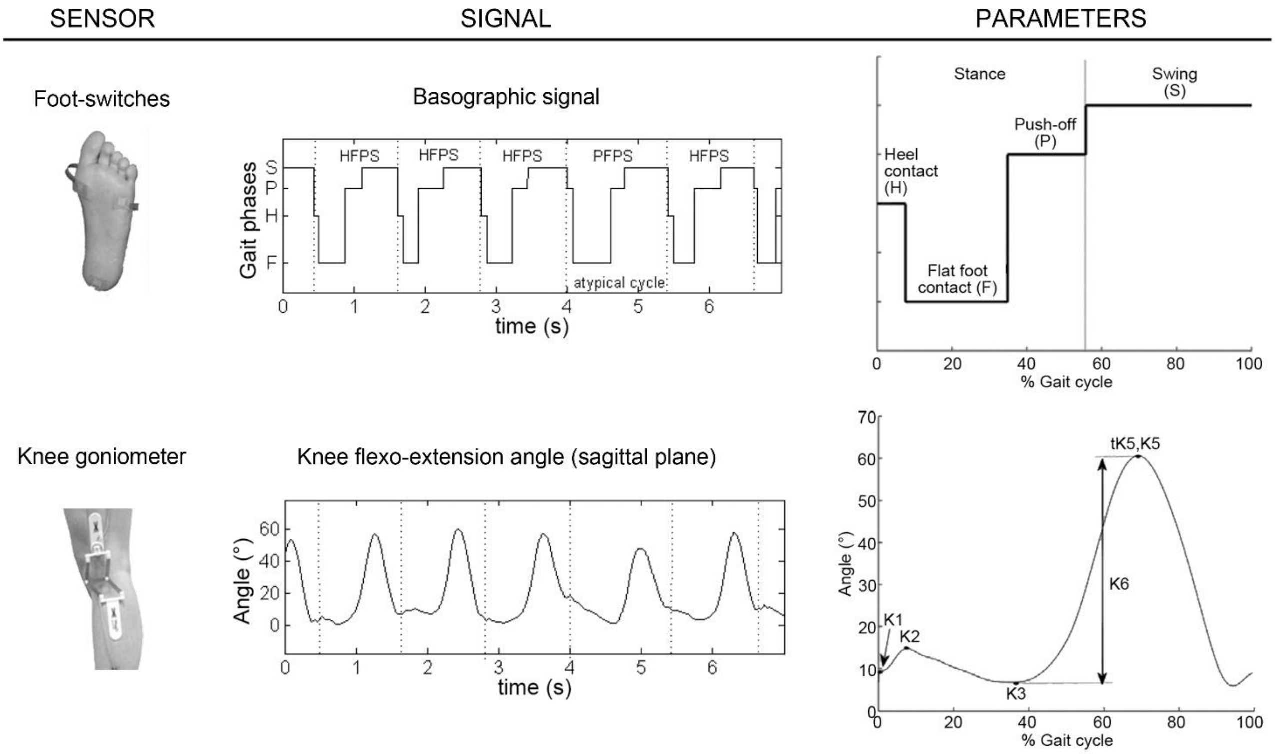
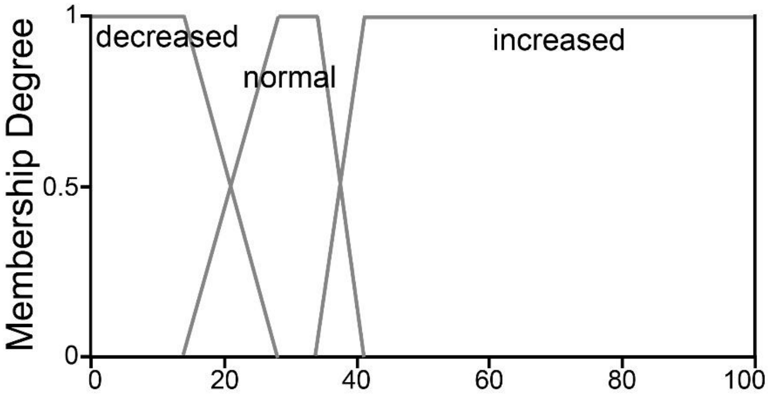
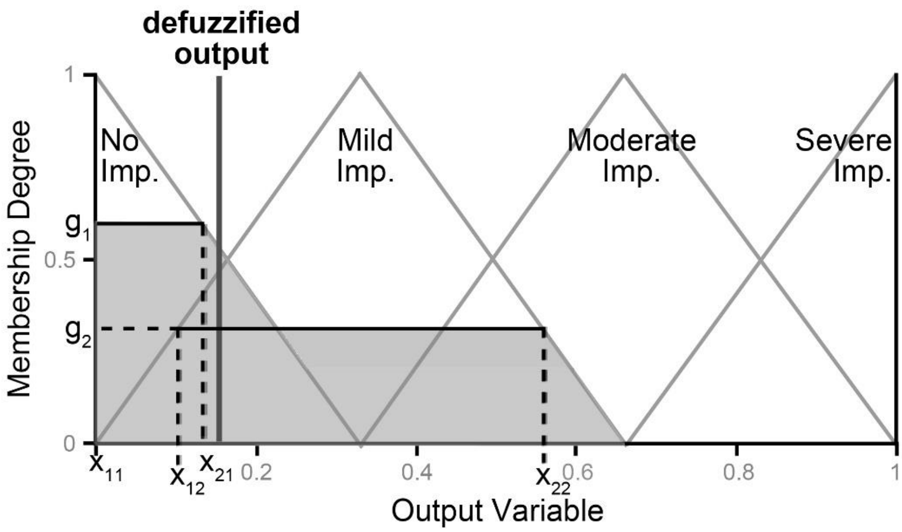


FIGURE 2



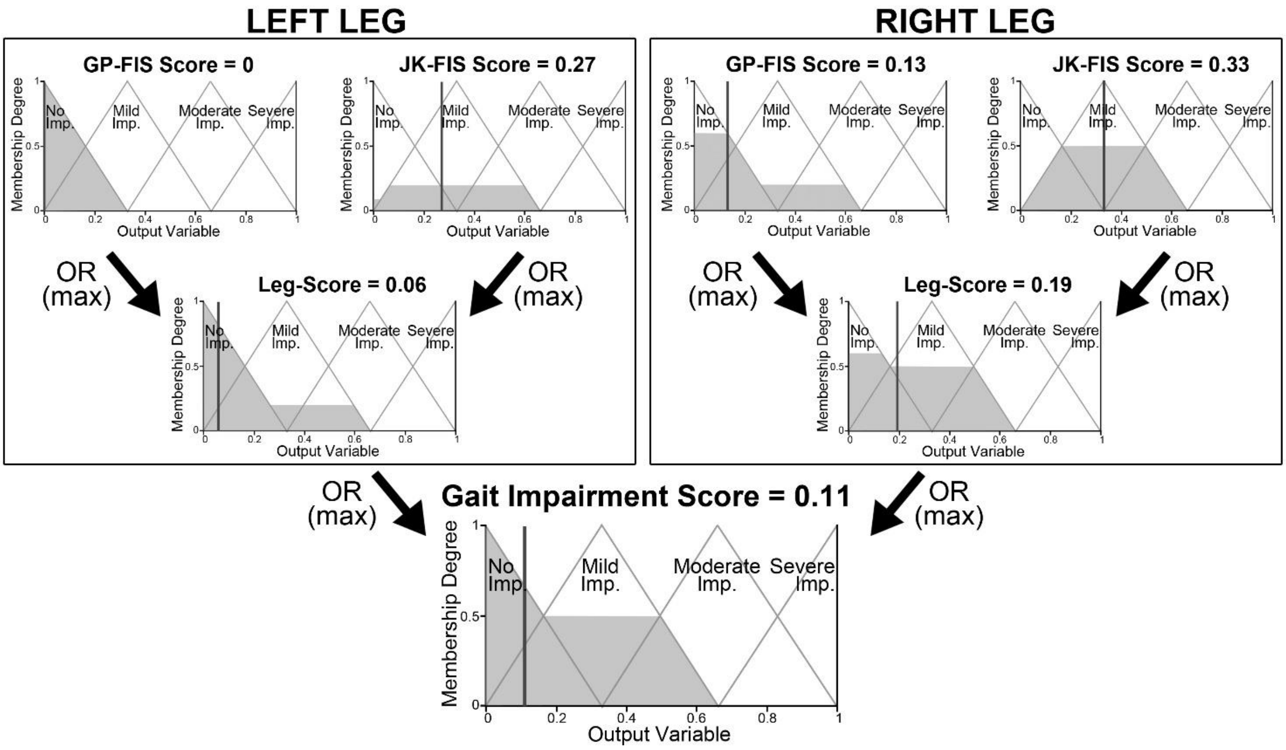
Membership Degree
1
0.5
0
decreased
normal
increased
0
20
40
60
80
100

FIGURE 3



defuzzified
output
1
No
Imp.
Mild
Imp.
Moderate
Imp.
Severe
Imp.
Membership Degree
g1
0.5
g2
0
x11
x12
x21
0.2
0.4
x22
0.6
0.8
1
Output Variable

FIGURE 4



LEFT LEG
RIGHT LEG
GP-FIS Score = 0
JK-FIS Score = 0.27
GP-FIS Score = 0.13
JK-FIS Score = 0.33
Leg-Score = 0.06
Leg-Score = 0.19
Gait Impairment Score = 0.11
OR (max)
No Imp.
Mild Imp.
Moderate Imp.
Severe Imp.
Membership Degree
Output Variable