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Fuzzy Set Theory For Cumulative Trauma Prediction

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Abstract

A widely used fuzzy reasoning algorithm was modified and implemented via an expert system to assess the potential risk of employee repetitive strain injury in the workplace. This fuzzy relational model, known as the Priority First Cover Algorithm (PFC), was adapted to describe the relationship between 12 cumulative trauma disorders (CTDs) of the upper extremity, and 29 identified risk factors. The algorithm, which finds a suboptimal subset from a group of variables based on the criterion of priority, was adopted to enable the inference mechanism of a constructed knowledge-based system to predict CTD occurrence.

Keywords: Fuzzy relation; Approximate reasoning; Cumulative trauma disorders; Priority cover; Expert systems

1 Introduction

Cumulative trauma disorders (CTDs) have been medically described since the 1890s, and have been associated with physical activities for nearly 300 years [5]. They are illnesses of the muscle, tendons, nerves, and other soft tissues, which are caused, aggravated, or precipitated by repeated exertions of the body [2].

The development of CTDs is attributed to certain factors that are both occupational and nonoccupational in nature. Among the occupational factors, repetitiveness, forcefulness, mechanical stresses, body posture, static muscle load, cold, and vibration appear to be most prevalent [1] [7]. Although it is not possible to determine the amount of physical stress required to precipitate or aggravate a cumulative condition, it is viable to identify and reduce the factors associated with tissue trauma. Several approaches, such as checklists, work standards, and biomechanical analysis, have been used in the identification of risk factors [3] [7].

During this research, fuzzy set theory was employed to assess the contribution of twenty nine occupational risk factors (Table 1) to the development of twelve common CTDs of the upper extremity (Table 2).

2. Relationship Between CTDs and Risk Factor

The assignment of relationship coefficients between a specific disorder and the factors associated with it represents a difficult and complicated undertaking. The existent research on the subject has not yielded yet a mathematical model for assigning quantitative or numeric values to the contribution of risk factors to the development of cumulative trauma.

Although attempts for quantifying the physical stress caused by the presence of specific occupational factors have constituted the approach followed by some researchers for assessing the likelihood of CTD occurrence [4] [6], such an approach is not very realistic. The approach employed in this study was the assignment of "discrete" values that describe the relationship between risk factors and CTDs in terms that most scholars can agree. After extensive research and interviewing of experts in the field of occupational ergonomics, the relationship between risk factors and CTD occurrence was finally assessed. Five different weighing factors were used to indicate the relationship between risk factors and precipitated disorders. If the risk factor was found to be very related to the development of the disorder under analysis, a value of 1.00 was assigned to the corresponding coefficient, 0.75 if moderately related, 0.50 if somehow related, 0.25 if not very related, and 0.00 if the risk factor was not related to the precipitation of the disorder at all.

3. Severity Level of Risk Factors

The severity level of a particular occupational risk factor varies according to the working environment and task demands. For instance, a particular job may involve the repeated lifting of numerous loads. In such a case, the severity level of the lifting action is determined by the weight of the loads as well as the frequency of the lifting. In this study, severity levels were stored as indices in a vector referred to as the *Severity Index* (***SI***) vector. This vector contains values between 0.00 and 1.00, where a severity index of 1.00 implies that the corresponding risk factor is severely involved in the execution of the task, while a value of 0.00 denotes the complete absence of the risk factor from the working environment.

TABLE 1
Risk Factors Considered in the Study

Use of a computer keyboard or typewriter
Prolong use of heavy tools
Frequent lifting with the palm down
Rotary motions of the wrist
Excessive use of a hammer
Repeated or forceful pronation of the forearm
Repeated or forceful supination of the forearm
Repeated or forceful flexion of the wrist

Repeated or forceful flexion of the thumb
Repeated or forceful flexion of the index finger
Forceful gripping
Ulnar deviation of the hand
Frequent or forceful flexion of the digits
Use of tools with sharp or hard edges
Use of small hand tools
Vibration
Excessive pressure on the palm of the hand
Repeated or forceful twisting motions at the elbow
Stressful posture of the wrist
Exposure to low temperatures
Hard or sharp resting of the forearm
Sustained shoulder reach
Use of gloves
Repetitive lifting of objects
Overhead work
Repetitive throwing actions
Forceful abduction of the arm
Frequent shoulder rotation and flexion

TABLE 2
Cumulative Trauma Disorders Considered in the Study

Lateral Epicondylitis
Medial Epicondylitis
de Quervain's Tendinitis
Trigger Finger
Pronator Teres Syndrome
Carpal Tunnel Syndrome
Cubital Tunnel Syndrome
Guyon's Canal Syndrome
Wrist Tendinitis
Rotator Cuff Tendinitis
Bicipital Tendinitis
Thoracic Outlet Syndrome

4. Possibility of Occurrence of Related CTDs

The model used to obtain the possibility of occurrence of upper extremity CTDs was first developed by Pandelidis and Kao [9]. This model was created for a relatively different application, a knowledge-based system for injection molding diagnostics [9]. However, due to the similarities in the nature of the knowledge handled by both systems, the model was considered appropriate for the prediction of CTDs.

The matrix ***FR*** contains the fuzzy relationship values arranged in twelve rows and twenty nine columns for the twelve CTDs and the twenty nine risk factors considered in the study. The vector ***SI*** indicates the severity indices of the twenty risk factors. Hence, the possibility of occurrence of all the CTDs (vector ***P***) is obtained by multiplying the matrix ***FR*** by the vector ***SI***. As it can be inferred, the vector of possibilities ***P*** may contain values greater than one [4].

To illustrate the scheme, consider a subset of 5 cumulative disorders, ***CD*** = {cd_1, cd_2, cd_3, cd_4, cd_5}, and 5 risk factors, ***RF*** ={rf_1, rf_2, rf_3, rf_4, rf_5}. The Fuzzy Relationship matrix (***FR***) consists of the different relationship coefficients between the five cumulative disorders and the five risk factors. Let these coefficient values be the following:

FR = (1)

	rf_1	rf_2	rf_3	rf_4	rf_5
cd_1	0.50	0.00	1.00	0.50	0.00
cd_2	0.75	1.00	0.00	0.25	0.00
cd_3	0.00	0.00	0.00	1.00	0.50
cd_4	1.00	0.50	0.00	1.00	0.00
cd_5	0.00	0.00	0.75	0.00	0.00

Let us suppose that the following severity level values have been specified for the risk factors rf_1, rf_2, rf_3, rf_4, *and* rf_5, respectively:

$$\boldsymbol{SI} = [0.90, 1.00, 0.00, 0.60, 0.20] \quad (2)$$

Then, the vector ***P*** containing the possibility values of all five CTDs is:

$$\boldsymbol{P} = \boldsymbol{FR} \times \boldsymbol{SI}^{t} = [0.75, 1.83, 0.70, 2.00, 0.00]^{t} \quad (3)$$

where the t superscripts indicate that matrix transposition is needed to make the multiplication possible.

This vector ***P*** indicates that among all five CTDs, cd_4 is the most likely to occur with a possibility of 2.00, followed by cd_2 with a possibility of 1.83, cd_1 with a possibility of 0.75, cd_3 with a possibility of 0.70, and cd_5 with a possibility of 0.00 (not likely to occur).

It is necessary to indicate that the numeric value of a possibility index does not provide an absolute measure of the likelihood of occurrence for the associated disorder. These indices are only relative values used to identify which CTDs are more likely to develop from a determined group of disorders. Through the knowledge of this information, it is possible to adopt corrective actions to reduce the severity level of the occupational risk factors that are more likely to precipitate a cumulative condition. Nevertheless, risk factors may overlap from disorder to disorder. Therefore, an optimizing algorithm, such as the Priority First Cover algorithm [9], must be employed to minimize the number of CTDs to be addressed.

5. Priority First Cover Algorithm

The Priority First Cover algorithm (PFC) was developed to find a suboptimal subset from a group of variables based on the criterion of priority. It was used by Pandelidis and Kao [9] in the development of their knowledge-based system for injection molding "DETECTOR”.

Nevertheless, the existence of a conceptual flaw embedded in the algorithm made it necessary to modify its original form prior to its implementation in this study. The Priority First Cover algorithm as originally stated by its developers is discussed as follows, as well as its revised version.

6. Original Priority First Cover Algorithm

Applied to the problem at hand, the Priority First Cover Algorithm consists of first creating an ordered, weighted list of CTDs, and then searching through the list until the first cover is obtained. The following steps are required to obtain the first cover:

(1) Arrange the CTD possibilities, vector $\boldsymbol{P}$, in descending order. The resulting ordered list will be denoted by $\boldsymbol{O} = \{cd^1, cd^2, cd^3, ...\}$ where cd^i is the i[th] disorder in the list.

(2) Let $\boldsymbol{PC}$ be the PFC set to be determined, and $\boldsymbol{PC}_j$ be the tentative cover in the i[th] step. The cumulative disorder with the highest possibility is selected first. Thus, $\boldsymbol{PC}_1 = \{cd_1\}$.

(3) At stage i, the disorder cd^i is added to the list $\boldsymbol{PC}_j$ if and only if it covers a new risk factor other than those previously covered (in accordance with the $\boldsymbol{FR}$ matrix), and has a possibility of occurrence greater than 0.00. Otherwise, the next disorder in the list is taken into consideration.

(4) The algorithm terminates when a cover has been found.

The example discussed in section 4 is used here to illustrate the PFC algorithm. The algorithm requires the use of the Fuzzy Relationship matrix and Possibility vector. These are shown once again to facilitate the analysis:

$\boldsymbol{FR} =$ (4)

	rf_1	rf_2	rf_3	rf_4	rf_s
cd_1	0.50	0.00	1.00	0.50	0.00
cd_2	0.75	1.00	0.00	0.25	0.00
cd_3	0.00	0.00	0.00	1.00	0.50
cd_4	1.00	0.50	0.00	1.00	0.00
cd_5	0.00	0.00	0.75	0.00	0.00

$$\boldsymbol{P} = [0.75, 1.83, 0.70, 2.00, 0.00]^t \quad (5)$$

<u>*Step 1:*</u>

Sort from $\boldsymbol{P} = [cd_1, cd_2, cd_3, cd_4, cd_5]$:
The resulting ordered list is $\{cd_4, cd_2, cd_1, cd_3, cd_5\}$

<u>*Step 2:*</u>

Put cd_4 into the set $\boldsymbol{PC}_1$ and record risk factor (cd_4) from the $\boldsymbol{FR}$ matrix

$$\boldsymbol{PC}_1 = \{cd_4\} \quad (6)$$

risk factor(cd_4) = $\{rf_1, rf_2, rf_4\}$

Step 3:

Check whether disorder (cd_2) = {rf_1, rf_2, rf_4} can cover a new risk factor or not. The disorder cd_2 is not added to $\boldsymbol{PC_1}$, because there is not a new risk factor.

Then, check whether disorder (cd_1) = {rf_1, rf_3, rf_4} can cover a new risk factor or not. The disorder cd_1 is added to $\boldsymbol{PC_1}$, because rf_3 is a new risk factor. Thus,

$\boldsymbol{PC_2}$ = {cd_4, cd_1 (7)

risk factor({cd_4, cd_1}) = {rf_1, rf_2, rf_3, rf_4}

Now, check whether disorder (cd_3) = {rf_4, rf_5} can cover a new risk factor or not. The disorder cd_3 is added to $\boldsymbol{PC_2}$ because rf_5 is a new risk factor. Thus,

$\boldsymbol{PC_3}$ = {cd_4, cd_1, cd_3} (8)

risk factor({cd_4, cd_1, cd_3})= {rf_1, rf_2, rf_3, rf_4, rf_5}

Step 4:

The algorithm stops here since no new risk factor can be added. The priority first cover for this example is then:

$\boldsymbol{PC}$ = {cd_4, cd_1, cd_3} (9)

The PFC algorithm, as originally stated, indicates that, in the examined case, cumulative trauma disorders cd_4, cd_1, and cd_3 constitute the prioritized set of CTDs to be addressed by the industrial ergonomist. This procedure should yield a cover that is the optimal solution, however, as it will be demonstrated in the next section, such a cover will not be obtained unless the PCF algorithm is modified.

7. Revised Priority First Cover Algorithm

The problem in the postulation of the original PFC algorithm resides in the fact that it does not consider the Severity Index matrix (***SI***) during the search for new risk factors to be covered. Therefore, a cumulative disorder may wrongly be added to the priority cover even though it covers a new risk factor with a severity index of 0.00 (not present in the working environment).

For instance, in the example discussed in the previous section, cumulative trauma disorder cd_1 was added to the priority cover because it covered rf_3, a new risk factor. However the Severity Index matrix $\boldsymbol{SI} = [0.90, 1.00, 0.0, 0.60, 0.20]^t$ reveals that rf_3 is not involved in the execution of the job (severity level index of 0.00). Hence, it is inappropriate to add cd_1 to $\boldsymbol{PC_1}$. The optimal priority cover for this example is then reduced to {cd_4, cd_3}.

Step 3 of the original FPC algorithm was modified to correct the existent flaw. The revised step 3 of the FPC reads as follows:

Step 3:

At stage i, the disorder cd_1 is added to the list $\boldsymbol{PC}_1$ if and only if it covers a new risk factor with a severity index greater than 0.00, other than those previously covered (in accordance with the ***FR*** matrix), and has a possibility of occurrence greater than 0.00. Otherwise, the next disorder in the list is taken into consideration.

8. Research Results

The relationship between CTDs of the upper extremity and associated risk factors was accessed and quantified through an approximate reasoning scheme, which represents an extension of the available research on CTDs prediction. A fuzzy set model, the Priority First Cover algorithm, was adopted and modified to determine the most likely cumulative conditions from a set of twelve potential disorders. Such a model constituted the logic mechanism of a computer expert system. The developed knowledge-based system was rigorously validated trough exhaustive evaluation of selected work scenarios [8]. During this validation process, it was demonstrated that the adopted fuzzy scheme was capable of generating results of the same caliber as the ones provided by real experts in occupational ergonomics [8].

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