An Application of Fuzzy Ergonomic Assessment for Human Motion Analysis in Modular Construction

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ABSTRACT

Work-related Musculoskeletal Disorders (WMSDs) account for about 34% of non-fatal injuries resulting in days away from work in the construction industry. Particularly in modular construction, due to the repetitive nature of the manual tasks, workers are highly exposed to ergonomic risks. To identify workers' awkward postures that potentially lead to WMSDs, ergonomic assessment tools have been developed and widely used by ergonomists and Occupational Health and Safety (OHS) practitioners. However, the accuracy of these methods is highly affected by the subjectiveness towards the user's inputs (e.g., body joint angles), which are difficult to accurately determine in given observation time. Consequently, the imprecise estimates of worker postures may result in inaccurate final results and risk intervention plans. In an effort to address this issue, this study applies fuzzy logic techniques to ergonomic evaluation tools—e.g., Rapid Upper Limb Assessment (RULA). By modelling the range of input values using fuzzy sets rather than discrete boundaries, the imprecision inherit in the inputs has less impact on the final RULA score. As a result, an automated fuzzy expert system has been developed by using membership functions and rules created based on the existing RULA method. An experiment is carried out in order to study the amount of imprecision in joint angle values from human estimations while observing a posture, and also to compare the sensitivity of RULA and the developed fuzzy RULA system to input imprecision. The results reveal that although the fuzzy RULA model has high correlation with RULA, it is more accurate and less sensitive to the variance in input values. The developed model presents a methodology to improve the accuracy of ergonomic assessment methods and handle the uncertainty inherent in ergonomic evaluation, providing the construction industry practitioners with an automated technique to evaluate the ergonomic safety of workers.

KEYWORDS

Modular construction, Ergonomics, Fuzzy logic, RULA, Work-related musculoskeletal disorder (WMSD), Construction worker safety.

INTRODUCTION

Modular construction has increasingly gained attention in the construction industry as a production method with lower cost, duration, waste and environmental impact compared to on-site construction (Inyang et al. 2012). However, due to the repetitive nature of manual tasks, workers in off-site construction are frequently exposed to physically challenging activities and ergonomic risk factors that can lead to Work-related Musculoskeletal Disorders (WMSDs) (Golabchi et al. 2015a). Despite the unsafety associated with manual handling tasks, production planners and facility managers typically tend to focus more on productivity improvements by redesigning the production process rather than on enhancing health and safety. This is mainly because the impact of productivity improvements can be observed shortly after production adjustments, while ergonomic safety considerations will benefit the construction companies in the long run. On the contrary, when safety precautions are not fully considered, the benefits of increased productivity are likely offset by the increased medical and workers' compensation costs resulting from WMSDs (Freivalds 2014). The prevention of WMSDs can be achieved primarily by reducing exposure to risk factors that may produce excessive physical stresses (i.e., beyond allowable human capacity) acting on the body (Radwin et al. 2001). Workers performing unsafe tasks are usually ignorant of the ergonomic risks associated with their actions, since it is difficult to be aware of the dangers and risks of motions leading to WMSDs that cumulatively develop over time. Therefore, managerial actions are required to identify and prevent the unsafe motions associated with manual tasks.

As one of the most effective approaches in reducing ergonomic risks, ergonomic assessment tools have been developed and are widely used to identify workers' awkward postures that potentially lead to WMSDs. These systems, also known as observation-based assessment methods, involve observing a worker's motions in order to identify unsafe postures and take corrective measures (NIOSH 2014). By taking into account the awkwardness of the worker's body posture as well as repetitiveness and duration of a manual activity, these assessment systems enable a quick, simple, and efficient analysis of ergonomic risks. However, the accuracy and reliability of the results of these methods depends on the precision of the inputs (e.g., body joint angles). As these inputs are usually obtained by ergonomists observing a worker performing a task, it is difficult to estimate accurate input values. As a result, the subjectiveness of the user inputs affects the reliability of the results of the analysis. This study evaluates the imprecision associated with human estimation of body joint angles and compares the subjectiveness of traditional ergonomic assessment tools with a fuzzy logic-based assessment system. To this end, one of the most widely used ergonomic assessment tools, Rapid Upper Limb Assessment (RULA) (McAtamney and Corlett 1993), has been investigated.

RESEARCH BACKGROUND

RULA, as well as most other posture-based ergonomic assessment tools, uses inputs describing the worker's posture, the force exerted on the worker's hands, and the repetitiveness of the task in order to analyze the level of ergonomic risks associated with a manual task and accordingly propose a corrective plan of action. The inputs required to define the human posture consists of joint angles of different parts of the worker's body (e.g., upper arm, wrist, trunk). In order to use a body joint angle as input for RULA, the user has to select one of the ranges of angles for that specific body part that consists of the joint angle. These joint angles are usually obtained by ergonomists and Occupational Health and Safety (OHS) practitioners through observing a worker performing a manual task in real time or from recorded video tapes and selecting the most awkward posture. As an example, Figure 1 shows the range categories for lower arm angle. For a manual task with the most awkward posture having a lower arm angle of 40°, the user has to use a score of 2 for the trunk, as shown in Figure 1. RULA defines similar range of angles for upper arm, wrist, neck, and trunk; the same process is carried out in order to obtain the score for each of these body segments. Muscle use and load score are also required as inputs which will be used in combination with the posture scores in order to calculate the final RULA score.

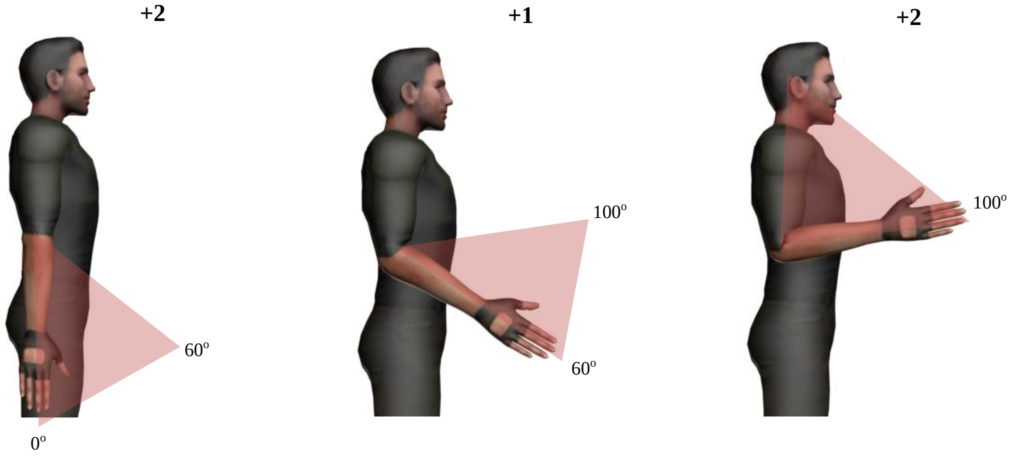


Figure 1. RULA Posture categories for lower arm

RULA is widely used as a simple and quick method of ergonomic assessment (Kee and Karwowski, 2007). It has been validated by the developers (McAtamney and Corlett 1993) through investigating the correlation between RULA scores and discomforts in body parts by analyzing subjects participating in a data entry operation. Despite the high correlation obtained from the experiment by using a Chi-Square (X^2) statistical test, discrepancies in RULA results occurred in cases where the posture to be analyzed consisted of a joint being located at a border between two ranges (McAtamney and Corlett 1993). The original posture categories for lower arm were modified, which might address the issue for activities such as data entry. However, workers in modular construction are typically involved in various manual handling tasks that consist of postures with different possible values of joint angles. Considering the approximation involved in estimating joint angles for a RULA analysis, discrepancy in final results can occur in case of analyzing postures with joint angles close to border of ranges which can reduce that accuracy and reliability of the ergonomic evaluation results. This discrepancy occurs due to using discrete boundaries between range of angles which results in abrupt change of score when moving from one range to another. Thus, a gradual transition between the angle ranges can address this issue and improve the reliability of the RULA method. The authors have proposed using fuzzy logic techniques to remodel the RULA system in order to reduce its subjectiveness towards the joint angles used as inputs (Golabchi et al. 2015b). This study thus mainly focused on the evaluation of the developed fuzzy logic system for ergonomic analysis of human postures through experiments.

FUZZY LOGIC-BASED ERGONOMIC ASSESSMENT

Fuzzy logic is a modeling technique that enables dealing with reasoning that is approximate rather than precise (Zadeh 1965). By using membership functions and if-then rules, fuzzy expert systems provide a framework to model uncertain and imprecise data through defining degrees of membership and gradual transition between classes of inputs. Due to these characteristics of fuzzy logic, it can be used to effectively redesign posture-based ergonomic assessment tools and prevent the discrepancy occurring as a result of sharp boundaries between ranges of joint angles. The authors have developed a fuzzy logic-based ergonomic analysis system, named Fuzzy RULA (Golabchi et al. 2015b). This paper investigates the amount of imprecision inherit in human estimation while observing a posture and studies Fuzzy RULA's subjectiveness towards this imprecision. A summary of the Fuzzy RULA model is presented below; for further information, readers are referred to Golabchi et al. (2015b).

Fuzzy RULA

The Fuzzy RULA model consists of 9 inputs, 4 intermediate variables, one final output, 5 rule blocks, 114 membership functions, and 371 if-then rules. Table 1 shows the components of the developed model. The inputs include the upper arm, lower arm, wrist, neck, and trunk angles, as well as wrist twist, force, and muscle use scores. These are the same set of inputs required for a RULA assessment. The score tables of RULA are used to develop if-then rules for the 5 rule blocks. An example of a rule derived from RULA's arm and wrist table is as follows:

- If upper arm score is 4 and lower arm score is 2 and wrist score is 3 and wrist twist score is 1, then arm and wrist score is 4.

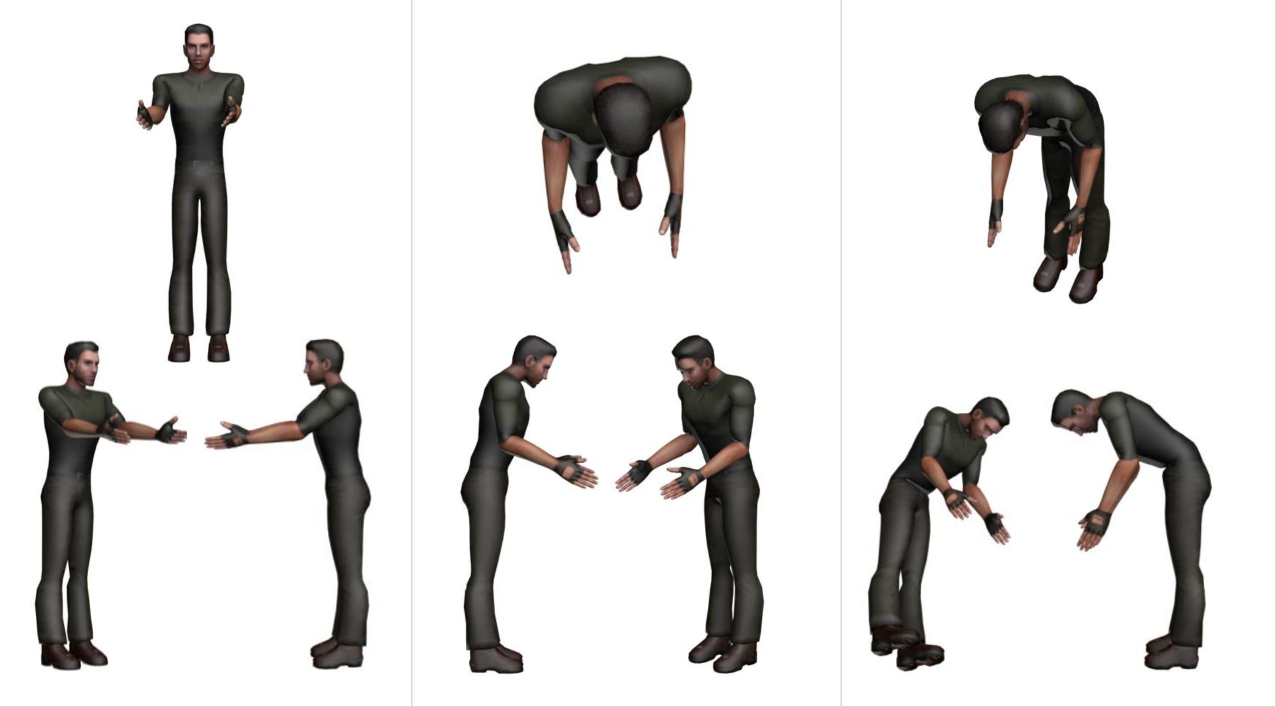
Table 1. Components of the Fuzzy RULA model

Input	Intermediate outputs		Final output
Upper arm angle	Posture score A	Arm & Wrist score	Fuzzy RULA score
Lower arm angle			
Wrist angle			
Wrist twist			
Muscle use			
Force			
Neck angle	Posture score B	Neck, Trunk & Leg score	
Trunk angle			
Leg			
Muscle use			
Force			

Membership functions of the inputs and outputs have been developed using a heuristic method. Linear membership functions are used due to their simplicity and also frequent application in fuzzy modeling. The membership functions are designed such that two adjacent sets intersect at a degree of membership of 0.5. Also, each point of intersection represents a border angle which enables a smooth transition between ranges of angles. Besides linear membership functions, the minimum operator for input aggregation, product operator for rule implication, bounded sum operator for rule aggregation, and fast center of area for defuzzification method are used. This system configuration yields the highest accuracy as it has the strongest correlation with objective measures of ergonomic risks (i.e., biomechanical analysis).

METHODS

An experiment is carried out in order to study the imprecision inherit in human estimation of joint angles while observing a posture and investigate its impact on the result of ergonomic analysis. Furthermore, the subjectiveness of RULA and Fuzzy RULA towards imprecise user inputs are compared. Fifty engineering students were trained on how to use RULA and were provided with 3D model representations of three postures shown from three different perspectives. The 3D models of the postures are shown in Figure 2. Their task was to report on the joint angles required as the inputs for RULA and perform a RULA analysis to calculate the total RULA score.



Posture 1 Posture 2 Posture 3

Figure 2. Three postures for RULA analysis

The three postures are designed such that the joint angle values of posture 1 are not very close to border of ranges, whereas posture 2 consists of joint angles very close to border of ranges and posture 3 consists of joint angle values somewhat close to border of angle ranges. The 3D models are created in a 3D modeling environment. The actual values of joint angles for each posture and other inputs required for RULA analysis as well as the final RULA score are provided in Table 2.

Table 2. Actual RULA inputs and output for the three postures

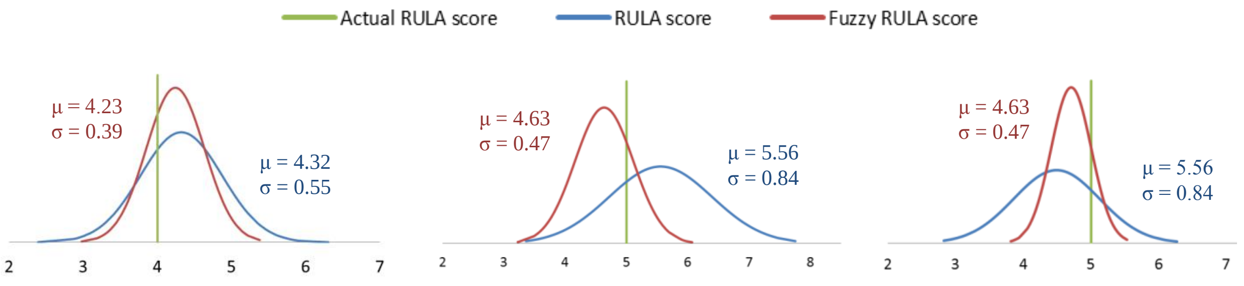
Posture	Upper Arm Angle	Lower Arm Angle	Wrist Angle	Wrist Twist Score	Muscle Use Score	Load	Neck Angle	Trunk Angle	Leg Score	RULA Score
1	60°	30°	0°	1	0	10 lb	0°	10°	2	4
2	21°	62°	14°	2	1	4.5 lb	19°	19°	1	5
3	-15°	50°	0°	2	0	5 lb	23°	65°	1	5

RESULTS AND DISCUSSION

Table 3 summarizes the data obtained from the subjects, showing the average and standard deviation of the joint angles as well as the RULA and FuzzyRULA scores. Figure 3 also shows a normal distribution representing the RULA and Fuzzy RULA scores using the calculated mean and standard deviation, as well as the actual RULA score. The x-axis represents the RULA and Fuzzy RULA scores and the y-axis represents the probability associated with the scores.

Table 3. Summary of results of experiment

Posture	Parameter	Upper Arm Angle	Lower Arm Angle	Wrist Angle	Neck Angle	Trunk Angle	RULA Score	Fuzzy RULA Score
1	**Average**	54.12°	32.10°	1.63°	6.66°	9.49°	4.32	4.24
	Standard deviation	9.82°	10.69°	3.77°	6.97°	4.54°	0.55	0.39
2	**Average**	9.80°	63.22°	3.76°	24.20°	18.83°	5.56	4.64
	Standard deviation	8.77°	12.92°	5.32°	9.03°	8.53°	0.84	0.48
3	**Average**	-1.64°	48.07°	0.55°	31.73°	54.11°	4.49	4.71
	Standard deviation	13.51°	15.45°	2.08°	12.98°	6.72°	0.63	0.30



Posture 1

Posture 2

Posture 3

Figure 3. Comparison of RULA and Fuzzy RULA distributions of the three postures

The following can be concluded from the results of the experiment:

(1) There is a high amount of imprecision involved in the estimation of joint angles by human observers. This is concluded by the values of standard deviations for the different body joint angles (e.g., 13.51° standard deviation for upper arm angle in posture 3). It should be noted that the variance from the actual value of joint angle will be higher than the values shown in Table 3 in case of observing human postures in real-time, where the user has to select the inputs in a short amount of time and also might not be able to view the worker posture from an ideal perspective, which will result in higher uncertainty regarding the joint angle values.

(2) Compared to the average of final RULA scores, the average of final Fuzzy RULA scores is closer to the correct RULA score for all the three postures. This indicates the high correlation between Fuzzy RULA and RULA. Furthermore, the standard deviation is smaller for Fuzzy RULA, which indicates that Fuzzy RULA is less affected by the scatteredness of the joint angle inputs. This is due to modeling the variables using membership functions that enable gradual transition between angle ranges, as opposed to using discrete boundaries in RULA.

(3) The standard deviation for posture 1, that was designed with joint angles not close to border of ranges, is less than that of posture 2 and posture 3. Posture 2 also has higher standard deviation from posture 3. On the other hand, the results of Fuzzy RULA analysis show smaller standard deviation in all three cases. This confirms the higher discrepancy of results of RULA analysis in cases of postures with inputs close to border of ranges and also the higher reliability of Fuzzy RULA in all cases.

CONCLUSION

Use of reliable ergonomic assessment methods enables evaluating the safety of workers in modular construction to identify and prevent ergonomic risks that can lead to WMSDs. Considering the imprecision inherit in human estimation of body joint angles used as inputs of posture-based ergonomic assessment tools, the subjectiveness of these tools towards the inputs can lead to discrepancy of final results. This paper quantifies the inaccuracy of human estimation of joint angles defining worker postures and investigates applying fuzzy logic modeling techniques to redesign ergonomic evaluation systems. The results confirm the high inaccuracy of human estimates and its effect on results of ergonomic analysis, and validate the use of fuzzy logic to reduce its impact. Using automated fuzzy expert systems for ergonomic assessment provides construction practitioners with a quick, simple, and reliable tool which can effectively identify unsafe worker actions and address them to reduce the rate of WMSDs.

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