

Assessing Physical Performance of Elders Using Fuzzy Logic

Shuang Wang, James M. Keller, Kathryn Burks, Marjorie Skubic, Harry Tyrer

Abstract—This paper describes the application of fuzzy logic to the Short Physical Performance Battery (SPPB) test, a series of timed physical activities that have been created to evaluate, discriminate, and predict physical functional performance for both research and clinical purposes, primarily for physically impaired older adults. The original scoring system of SPPB test uses crisp time boundaries to assign the subject to discrete classes of performance. The crisp (and somewhat arbitrary) nature of the crisp thresholds can easily produce anomalies. Fuzzy Logic theory allows the natural description, in linguistic terms, of input/output relationships rather than relying on precise numerical threshold values. This advantage, dealing with the complicated systems in simple way, is the main reason why fuzzy logic theory is widely applied. In this paper, we offer a new approach for scoring the SPPB test. We demonstrate that in the proposed system, the Fuzzy Short Physical Performance Battery (FSPPB), we can improve the sensitivity and data distribution of the scoring system for the SPPB test. We present the procedures of constructing a fuzzy inference system using fuzzy logic to score the SPPB test and compare the original scoring system with our fuzzy scoring system. As part of a large project in technology for Eldercare, our goal is to accurately measure trends in physical performance of seniors over time.

Keywords—Fuzzy logic, Short physical performance battery test, Eldercare technology

I. INTRODUCTION

Older adults are living longer and more fulfilled lives, and they desire to live as independently as possible in the home of their choice. However, independent lifestyles come with risks that are complicated by chronic illness and impairments in mobility, cognition, and the senses. In response to this trend, the University of Missouri has been investigating new approaches in caring for the elderly. One recent example of this research focus has resulted in TigerPlace, a 32-unit apartment complex for seniors that opened in Columbia, Missouri in 2004. A joint venture between MU's Sinclair School of Nursing and Americare Systems Inc., TigerPlace is one of four projects granted state approval to operate under the "aging in place" model of care giving [1]. Under that model, residents who would otherwise be required by state law to live in nursing homes may have health services brought to them in their apartments instead.

Technology that can help seniors "age in place" has been spotlighted in recent years, spurred by an aging population. One focus of our research is the creation of "intelligent software" that uses sensors to uncover patterns of activity helpful to caregivers [2], especially targeting mobility and

cognitive impairment. Details can be found at <http://eldertech.missouri.edu>. A critical part of this effort is being able to sense, detect and assess changes in basic physical performance in elders. So, we centered on the *Short Physical Performance Battery* (SPPB) test [3]. This exam was created to evaluate, discriminate, and predict physical functional performance for older adults. It was used to assess lower extremity function in more than 5,000 persons age 71 years and older. The SPPB test measures balance, gait, strength, and endurance. Although it is a timed performance test, each subtask score is an integer value in the range 0-4. A score of 0 indicates the inability to complete the task in a nominal time frame while categories 1-4 are assigned to the corresponding quartiles of time needed to perform the action. There are five subscales: semi-tandem standing (the heel of one foot on the side of the big toe of the other foot), side by side standing, full tandem position (the heel of one foot directly in front of the other foot), walking speed (eight feet on a smooth service with no obstructions), and a sit-to-stand test (rise from a chair five times with arms folded across the chest). It has been shown that such performance measures correlate well with the self-assessment of older persons across a broad spectrum of lower extremity function [3-6]. The original scoring for the SPPB test is as follows [3]:

Scoring performance on tests of standing balance

Score	Side by side stand	Semi-tandem stand	Full tandem stand
0	t < 10 seconds	Not attempted	Not attempted
1	t = 10 seconds	t < 10 seconds	Not attempted
2	t = 10 seconds	t = 10 seconds	t < 3 seconds
3	t = 10 seconds	t = 10 seconds	3seconds <= t < 10seconds
4	t = 10 seconds	t = 10 seconds	t = 10 seconds

Scoring performance on test for walking 8 feet (using faster of the two walks)

Score	Walking Time
1	t >= 5.7 seconds
2	4.1seconds <= t <= 5.7seconds
3	3.2seconds <= t < 4.1seconds
4	t < 3.2seconds

Scoring performance on chair test (sit to stand 5 times)

Score	Sit to Stand Time
1	t >= 16.7 seconds
2	13.7seconds <= t < 16.7seconds
3	11.2seconds <= t < 13.7seconds
4	t < 11.2seconds

While the crisp scoring of the SPPB has been validated on good sized populations of elders, the crisp nature of the

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S. Wang, J. Keller, M. Skubic and H. Tyrer are with the Electrical and Computer Engineering Department, University of Missouri- Columbia, Columbia, MO 65211. J. Keller is the corresponding author (kellerj@missouri.edu, (573) 882-7339).

K. Burks is with the Sinclair School of Nursing, University of Missouri-Columbia, Columbia, MO 65211.

judgment leads to common anomalies near threshold boundaries and does not possess a fine enough granularity to be used within a frequent automated evaluation of the physical capabilities of a particular senior. Hence, the goal of this paper is to produce and analyze a fuzzy logic rule-based system that preserves the original design of the SPPB but addresses these two shortcomings.

Fuzzy logic has attracted the attention of several researchers in health care. Fuzzy logic provides a methodology that simulates human thinking by explicitly modeling and managing the imprecision and uncertainty inherent in health assessment, grade of membership methods are employed to summarize functional status, and multinomial logit models provide information on the association between biological measures and function [7]. On Lok used grade-of-membership analysis, to classify participants on the basis of their specific diseases, impairments, and disabilities [8]. Other studies in this field use grade of membership methods to evaluate health and mortality of the elderly [9], to analyse medical, behavioral, psychosocial, and characteristics of service use by nursing home residents [10], and to classify taste responses in brain stem [11]. Still others use fuzzy logic in aging research [12].

II. DESIGN OF A FUZZIFIED SCORING SYSTEM FOR THE SPPB TEST

A. Design Criteria

A typical fuzzy logic system has four components: a fuzzifier, a fuzzy rule base, an inference engine, and a defuzzifier. The function of the fuzzifier is to determine the degree of membership of a crisp input in a fuzzy set. The fuzzy rule base is used to represent the fuzzy relationships between input-output fuzzy variables. The output of the fuzzy rule base reflects the degree of membership specified by the fuzzifier. The inference engine calculates the rule's conclusion based on its membership degree. A defuzzifier is used to convert outputs of the fuzzy rule base into crisp values. Figure 1 illustrates a block diagram of a fuzzy system.

For the SPPB test, there are three parts in the original scoring system, standing balance score, walking test score and chair test score. The overall flow chart of the implementation is shown in Figure 1. Fuzzy set theory offers us a wide variety of aggregation operators (including a fuzzy logic system) to combine the outputs of the three tests. However, because there is no standard for interpreting the sum of the test scores in the SPPB, we have not investigated a fuzzy aggregation to date.

A potential problem with aggregating these separate scores is that the tests are not completely independent. For example, the first physical performance test in the battery measures balance; however, subsequent test performance is also influenced by balance. In addition, the balance test is not as sensitive to variations in scoring because it is time-limited (a maximum of 10 seconds in each position). By summing the scores in to an aggregate score, we risk losing overall sensitivity. As a result, we look at individual sub-task scores using fuzzy logic and do not perform the aggregation in this study.

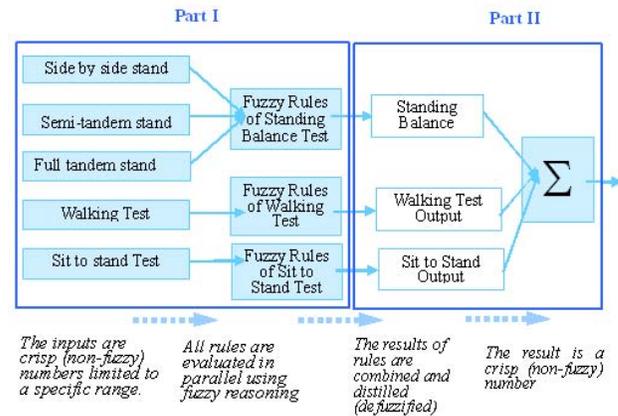


Figure 1. Overall Flow Chart of Fuzzy Scoring Implementation

B. Choice of Membership Functions

Based on a review of the data and discussions with the nursing members of our team, for the fuzzified scoring system of SPPB test, we needed membership functions with characteristics of smoothness, asymmetry, zero on both extremes with a quick rise in the middle. Pi curves, as shown in Figure 2, satisfy our requirements.

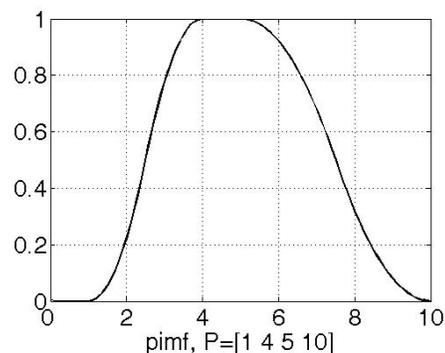


Fig. 2. Pi Membership Function

A Pi membership function is determined by 4 parameters $P_i [a,b,c,d]$. The parameters a and d locate the "feet" of the curve, while b and c locate its "shoulders." The linguistic variables for our rule-based system are the same as for the original SPPB test. The linguistic values were created to model the crisp threshold ranges in [3]. Specific choices for membership functions to model the linguistic values were chosen experimentally (at this point) with an eye to soften the harsh boundaries while preserving the general flavor of the performance ranges from the standard scoring approach.

From Figure 1 we see that there are three inputs and one output in the standing balance test. Hence, we need linguistic values and membership functions for side by side stand, Semi-tandem stand, and full tandem stand. Figure 3 displays the linguistic values for the three linguistic variables along with specific membership functions for the standing balance test as determined for this experiment. For all membership functions, the abscissa represents time in seconds to complete the task.

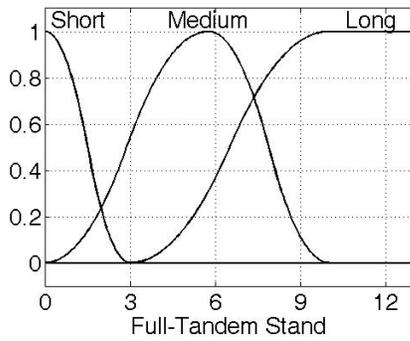
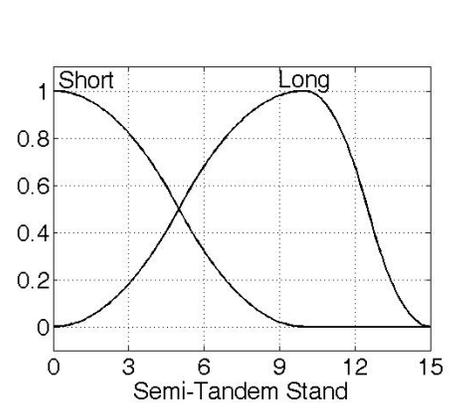
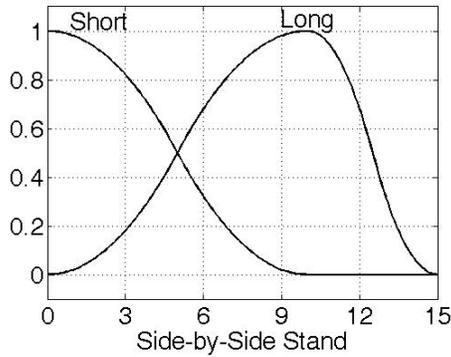


Fig. 3. Membership Functions of Standing Balance Test

These functions were determined experimentally to preserve the meaning of the scoring categories while softening the boundaries.

In Figure 1 there is one input and one output in the walking test. The linguistic values with their membership functions are graphically displayed in Figure 4.

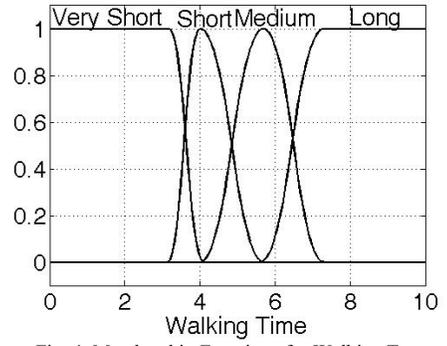


Fig. 4. Membership Functions for Walking Test

In the sit to stand test also, there is one input and one output. Figure 5 shows the linguistic values and their membership functions for this test.

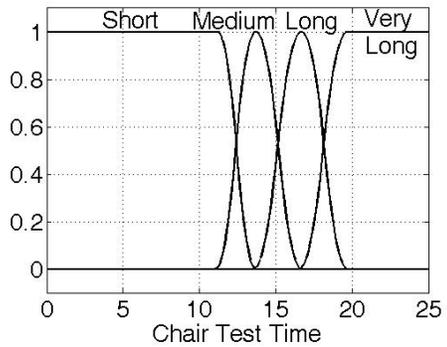


Fig. 5. Membership Functions of Chair Test

C. Fuzzy Rules Decision

The fuzzy rules for the soft SPPB test should be decided by the nursing specialist based their knowledge, experience and expectations. Through experimentation, the rules for our initial prototype fuzzy logic system are the following.

Fuzzy Decision Rules for Balance Test

1. If (Side-by-Side_Stand_Time is SHORT) then (Standing_Test_Performance is VERY_POOR)
2. If (Side-by-Side_Stand_Time is LONG) and (Semi-Tandem_Stand_Time is SHORT) then (Standing_Test_Performance is POOR)
3. If (Side-by-Side_Stand_Time is LONG) and (Semi-Tandem_Stand_Time is LONG) and (Full-Tandem_Stand_Time is ShortSHORT) then (Standing_Test_Performance is OK)
4. If (Side-by-Side_Stand_Time is LONG) and (Semi-Tandem_Stand_Time is LONG) and (Full-Tandem_Stand_Time is MEDIUM) then (Standing_Test_Performance is GOOD)
5. If (Side-by-Side_Stand_Time is LONG) and (Semi-Tandem_Stand_Time is LONG) and (Full-Tandem_Stand_Time is LONG) then (Standing_Test_Performance is EXCELLENT)

Fuzzy Decision Rules for Walking Test

1. If (WalkingTime is VERY_SHORT) then (Walking_Test_Performance is EXCELLENT)
2. If (WalkingTime is SHORT) then (Walking_Test_Performance is GOOD)
3. If (WalkingTime is MEDIUM) then (Walking_Test_Performance is OK)
4. If (WalkingTime is LONG) then (Walking_Test_Performance is POOR)

Fuzzy Decision Rules for Sit to Stand Test

1. If (Chair_Test_Time is SHORT) then (Chaire_Test_Performance is GOOD)
2. If (Chair_Test_Time is MEDIUM) then (Chaire_Test_Performance is OK)
3. If (Chair_Test_Time is LONG) then (Chaire_Test_Performance is POOR)
4. If (Chair_Test_Time is VERY_LONG) then (Chaire_Test_Performance is VERY_POOR)

D. Choice of fuzzy inference system

The most popular models of fuzzy inference systems are the Mamdani models [13] and the Takagi-Sugeno-Kang (TSK) models [14]. The main difference between them is the consequent part of fuzzy rules. The Mamdani models describe the consequent part using the linguistic variables, while the Takagi-Sugeno-Kang models use the linear combination of the input variables. Both models use linguistic variables to describe the antecedent part of fuzzy rules. For the fuzzified scoring system of SPPB test, we use a Sugeno inference system.

III. RESULTS AND ANALYSIS

This fuzzy rule-based scoring system of SPPB test was developed with the Fuzzy Logic Toolbox of MATLAB [15]. We use data from Dr. Kathryn Burks, School of Nursing, University of Missouri-Columbia to test the fuzzy scoring system of SPPB test [16]. The data corresponds to the SPPB times recorded from 43 older adults with and without osteoarthritis of the knee collected as a part of a larger study. Figures 6, 7, and 8 display the output values for both the crisp and fuzzy scoring of the SPPB. Each figure has two parts. The first lists crisp and fuzzy scores for each subject for the individual tests while the second part shows the output of both scoring methods as a function of the input parameters.

The following symbols are used in Figures 6-8.

- | | |
|--------------------------|-----------------------------|
| ○ Fuzzy Score of Class 4 | ● Original Score of Class 4 |
| □ Fuzzy Score of Class 3 | ■ Original Score of Class 3 |
| △ Fuzzy Score of Class 2 | ▲ Original Score of Class 2 |
| ▽ Fuzzy Score of Class 1 | ▼ Original Score of Class 1 |

Fuzzy and Original Balance Score Comparison

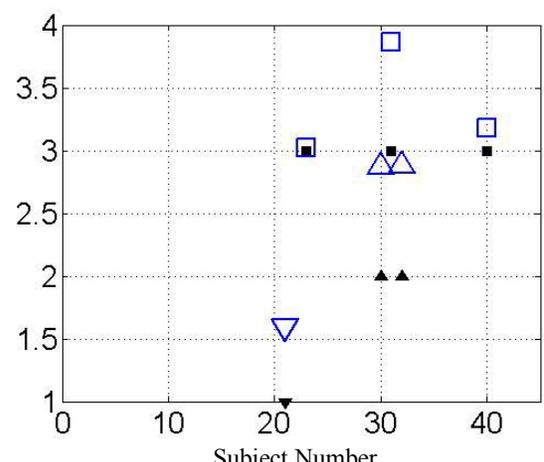
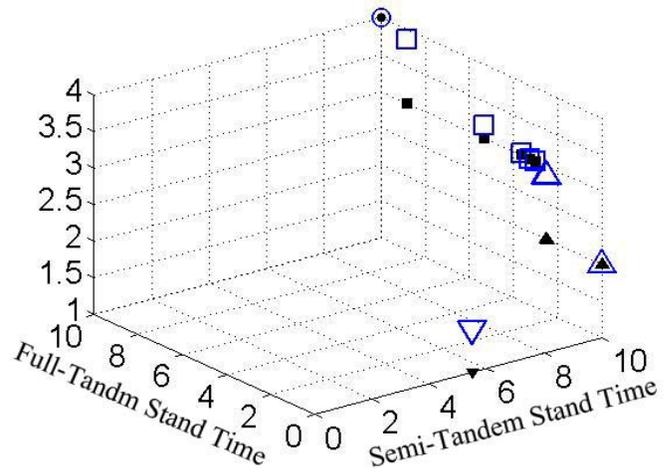
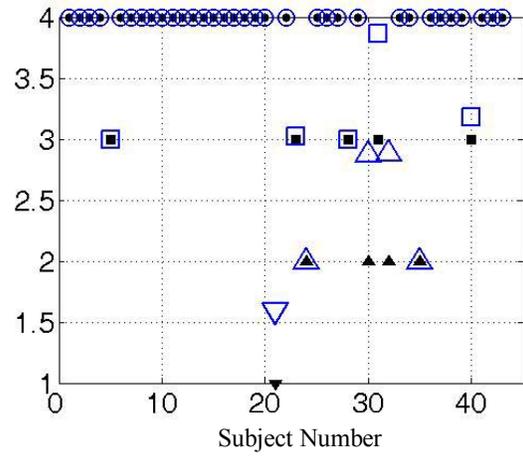
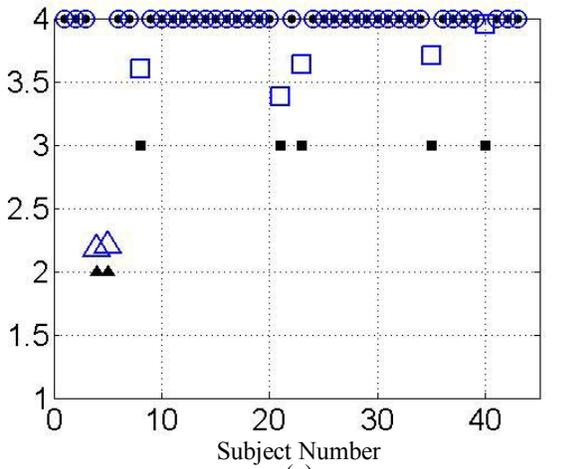
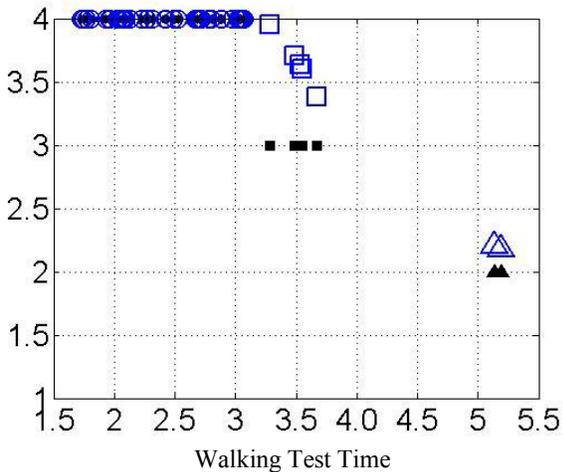


Figure 6. Comparisons of Fuzzy Balance Score and Original Balance Score; (a) viewed as function of subject, (b) viewed as function of input parameters, (c) only subjects with different fuzzy and original balance score are shown.

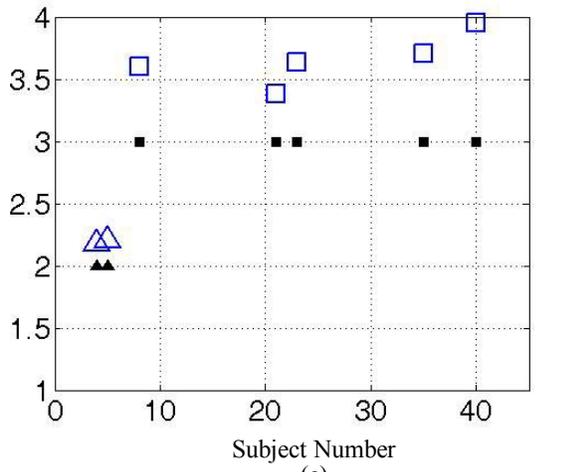
Fuzzy and Original Walking Test Score Comparison



(a)



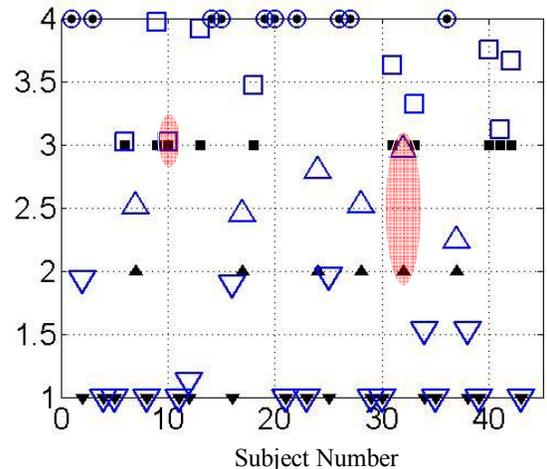
(b)



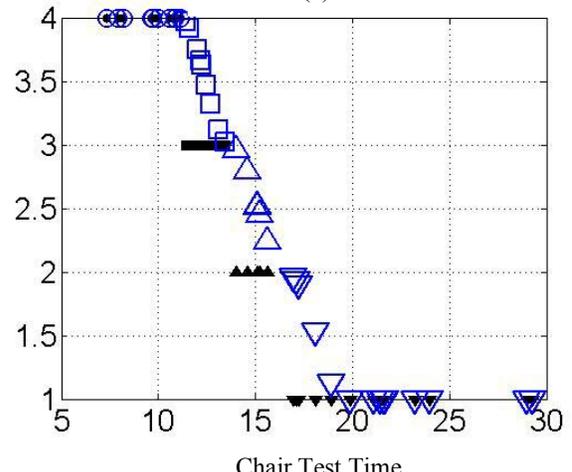
(c)

Figure 7. Comparisons of Fuzzy Walking Test Score and Original Walking Test Score; (a) viewed as function of subject, (b) viewed as function of input parameters, (c) only subjects with different fuzzy and original balance score are shown.

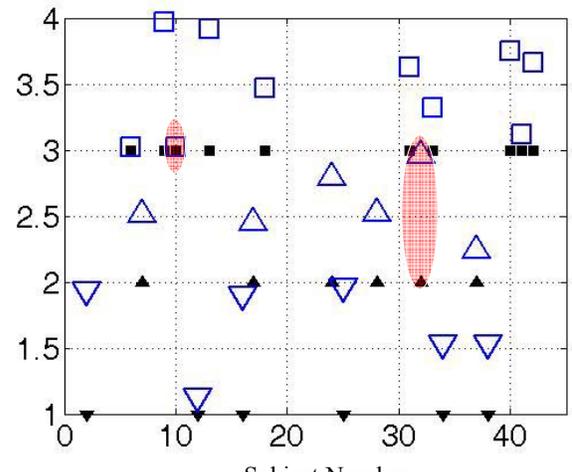
Fuzzy and Original Chair Test Score Comparison



(a)



(b)



(c)

Figure 8. Comparisons of Fuzzy Chair Test and Original Chair Test Score; (a) viewed as function of subject, (b) viewed as function of input parameters, (c) only subjects with different fuzzy and original balance score are shown.

In many cases, the crisp and fuzzy scoring are consistent, with the fuzzy scores close to the integer crisp classification. This is particularly true for the balance test, where most

subjects received 4.0 scores, a potential cause for confusion if the scores from the three subtests are simply added. This situation also indicates that the fuzzy scoring preserves the essential meaning of the SPPB for persons who are “nominal” members of the crisp classes. The fuzzy scores gradually deviate from the crisp number as the subject’s time moves towards the threshold boundaries. The real differences can be seen near the boundaries of the time thresholds. For the few cases in the balance test where the crisp and fuzzy scoring differ (figure 6(c)), the fuzzy score is higher than the standard, indicating somewhat better balance than what is reflected in the crisp score. In the sit-to-stand test, subject 10’s time was 13.44 sec. while that for subject 32 was 13.99 sec. These are highlighted in Figure 8(a). Within the time range allowed for this test, there is little difference between these two times and yet the crisp scores are 3 and 2, respectively, indicating a substantial difference in performance. Our fuzzy scoring system produces values of 3.02 and 2.96, conveying to the caregiver the nearness of the relative physical performance. From the standpoint of frequent automated analysis of physical performance, having gradual scores provides better information to the caregiver to monitor changes in an elder’s physical capabilities, allowing for timely intervention and perhaps suggesting some physical therapy to slow the decline before it becomes drastic. Crisp class labels then can still have a nominal meaning but allow for shades of gray to indicate how far from the “prototype” member of that physical category a particular elder performs. Also, higher performance vs. lower performance within a category is made obvious. Figures 6(c), 7(c), and 8(c) show the number of deviations from the crisp categories.

The fuzzy scores on the SPPB provide more sensitive information regarding the status of physical performance in these individuals than was previously available. This is especially true for the sit-to-stand test. In the first two tests, there is only one score of 1, whereas the sit-to-stand test shows 17 subjects whose crisp score is 1 (Figure 8 (c)). The fuzzy scores in Figure 8 (b) have more variability, indicating partial loss of physical performance potentially at an earlier stage. This soft scoring might be a mechanism to start a treatment intervention that will slow the loss of functionality.

IV. CONCLUSIONS

The major goal of our extended research team is to introduce advanced sensors, novel signal/image processing, and high level reasoning to enhance the independence and safety of older people while maintaining privacy and minimizing interference. Our goal is consistent with Zadeh’s definition of Recognition Technology to provide a “quantum jump in the capabilities of today’s recognition systems” [17]. Keeping track of the day-to-day physical performance capabilities plays a major role in this effort. One of the benchmark methods for measuring such performance is the Short Physical Performance Battery. Since we will be able to perform similar measurements frequently, though perhaps with more variation than is seen in the caregiver assisted exam, a more robust method of scoring, with finer sensitivity, is needed. This work represents the first movement in that direction. Using a TKS fuzzy rule base, we demonstrated a

scoring system that better reflects the actual performance of individuals on a small data sample and demonstrated increased sensitivity to classical threshold boundaries.

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