A Novel Model for Metabolic Syndrome Risk Quantification Based on Areal Similarity Degree

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***Abstract*—Metabolic syndrome (MS) refers to a clustering of specific cardiovascular disease (CVD) risk factors whose underlying pathology is thought to be related to insulin resistance. The risk factors include insulin resistance, obesity, dyslipidemia, and hypertension and it is known to increase the risk for CVD and type II diabetes. Since MS helps to identify individuals at high risk for both CVD and type II diabetes, it has become a major public healthcare issue in many countries. There has been much effort to establish diagnostic criteria for MS, but the current diagnostic criteria of MS have weaknesses, such as binary decision based on diagnostic criteria, equal weight among risk factors, and difficulty in estimating the temporal progress of the risk factors. To resolve these problems, this paper proposes a risk quantification model for MS, which is based on areal similarity degree analysis between weighted radar charts comprising MS diagnostic criteria and examination results of risk factors. The clinical effectiveness of the proposed model is extensively evaluated by using data of a large number of subjects obtained from the third Korea National Health and Nutrition Examination Survey. The evaluation results show that the proposed model can quantify the risk of MS and effectively identify a group of subjects who might be classified into a potential risk group for having MS in the future.**

***Index Terms*—Cardiovascular disease (CVD), chronic disease, healthcare, metabolic syndrome (MS), type II diabetes.**

I. Introduction

METABOLIC syndrome (MS) has become a major public healthcare issue in many countries. MS refers to a cluster of specific cardiovascular disease (CVD) risk factors whose underlying pathology is thought to be related to insulin resistance. Those risk factors include insulin resistance, obesity, dyslipidemia, and hypertension and they are thought to increase the risk for CVD and type II diabetes mellitus (T2DM). Therefore, the importance of MS is that it helps to identify individuals at high risk for both CVD and T2DM [1], [2].

There has been much effort to establish diagnostic criteria for MS among several expert groups such as the World Health Organization (WHO), the European Group for the Study of Insulin Resistance (EGIR), the National Cholesterol Education Program—Third Adult Treatment Panel (NCEP ATP III), the American Association of Clinical Endocrinologists, American Heart Association—National Heart, Lung, and Blood Institute (AHA/NHLBI), and the International Diabetes Federation (IDF). Table I summarizes the current definitions of MS [3]. All the diagnostic criteria include obesity, insulin resistance, dyslipidemia, and hypertension as the critical risk factors of MS. However, the detailed definition and thresholds for each critical risk factor are different, so the existence of multiple definitions for MS has caused confusion, and it has proved difficult to make direct comparisons between studies in which different definitions were used to identify the syndrome or the data from different countries. Therefore, many studies are being performed to develop a consensus about the definition and thresholds for diagnostic criteria so as to acquire more accurate diagnosis [1].

There have been many studies to investigate the risk factor structure of MS, the prevalence of MS, the impact of the risk factors in the development of MS, and the relationship between MS and other diseases. Some of these studies are found in [4]–[8]. Also, there is another approach to investigate the mechanism of MS from the microscopic perspective at the cell and mitochondria level [9]–[11]. Those previous studies have mostly aimed to analyze the effects of individual risk factors on MS, but due to the clustering characteristics of MS, it is necessary to take a holistic approach for a more accurate understanding of MS. Multivariate analysis has shown that the individual risk factors comprising the syndrome each carry different odds ratios for predicting the prevalence of coronary heart disease (CHD), the incidence of CHD, and CVD mortality. Some of the previous studies have shown that the identification of individuals with MS may provide opportunities to intervene earlier in the development of shared disease pathways that predispose individuals to CHD, CVD, and T2DM [12], [13]. In addition to hyperglycemia, low high-density lipoprotein (HDL) cholesterol and hypertension usually indicate a significantly greater risk compared with the presence of obesity or high triglycerides [14], [15]. The studies also illustrate another likely shortcoming of the current

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TABLE I
MS DEFINITIONS

		WHO (1999)	EGIR (1999)	NCEP ATP III (2001)	IDF (2006)	AHA/NHLBI (2005)
Diagnostic criteria		Glucose intolerance, IGT or diabetes and/or insulin resistance together with two or more of the following:	Insulin resistance together with two of the following:	Three or more of the following five risk factors:	Obesity and two or more of the following four risk factors:	Three or more of the following five risk factors:
Risk factors	FG		≥ 110 mg/dl but non-diabetic	≥ 110 mg/dl but non-diabetic	≥ 100 mg/dl or treatment	≥ 100 mg/dl or treatment
	BP	≥ 140/90 mmHg	≥ 140/90 mmHg or treatment	≥ 130/85 mmHg	Systolic: ≥ 130 mmHg or Diastolic: ≥ 85 mmHg or treatment	≥ 130/85 mmHg or treatment
	TG	Raised plasma triglycerides: ≥ 150 mg/dl and/or	> 178 mg/dl or treatment and/or	≥ 150 mg/dl	≥ 150 mg/dl	≥ 150 mg/dl or treatment
	HDL-C	Male: < 35 mg/dl Female: < 39 mg/dl	< 39 mg/dl or treatment	Male: <40mg/dl Female: <50mg/dl	Male: < 40 mg/dl Female: < 50 mg/dl or treatment	Male: <40mg/dl Female: <50mg/dl or treatment
	Obesity	Male: WHR > 0.9, Female: WHR > 0.85 and/or BMI > 30 kg/m2	Male: WC ≥ 94cm Female: WC ≥ 80cm	Male: WC > 102 cm Female: WC > 88 cm	Country/ethnic specific values for WC	Male: WC > 102 cm Female: WC > 88 cm
	Microalbuminuria	Urinary albumin excretion rate ≥ 20μg/min or albumin/creatine ratio ≥ 30mg/g				

IGT, impaired glucose tolerance; FG, fasting glucose; BP, blood pressure; TG, triglycerides; HDL-C, high-density lipoprotein cholesterol; WHR, waist-hip ratio; WC, waist circumference; BMI, body mass index

approach to diagnosing MS. All the NCEP ATP III, WHO, and AHA/NHLBI definitions weigh each risk component equally, yet it is clear that some risk factors included in the definitions have greater CVD predictive value than others. This fact is highlighted in other algorithms used to predict CVD risk using regression coefficients to assign different weights to risk factors [16], [17], and it is apparent from studies that examined the risk of CVD in persons with one or two components of MS versus three or more [18].

According to these studies, MS should be considered a progressive process that leads to major complications over time. Its expression depends heavily on age and exposure to an unhealthy lifestyle. Diagnosis of MS should not be managed as an acute infection, and a binary decision based on a yes or no approach is not valid in chronic degenerative disorders such as MS. MS incorporates clinical entities in which insulin resistance plays a major pathological role. This concept results in a group of subjects with a spectrum of long-term risk for having the final outcomes. The risk depends on the characteristics of the population being examined. Future adaptations to the current definitions of MS should take into account ethnic variability. Selection of diagnostic thresholds should be supported by the risk for developing major complications, especially if treatment can prevent these outcomes. The following case is a typical example to show the weakness of current MS diagnostic criteria. A 55-year-old man who had a body mass index of 27 kg/m^2, a waist circumference of 98 cm, HDL-cholesterol of 36 mg/dl, triglycerides of 180 mg/dl, fasting glucose of 90 mg/dl, postchallenge 2 h glucose of 180 mg/dl, fasting insulin of 32 μU/ml, and a blood pressure of 120/80 mmHg is not determined to have MS by either the NCEP ATP III or the WHO definition, despite the presence of insulin resistance, impaired glucose tolerance, hypertriglyceridemia, low HDL-cholesterol, and overweight [2], [5].

The weaknesses of the current diagnostic criteria of MS can be summarized as follows.

1) No consideration for different importance among risk factors.
2) Thresholds-based binary style diagnosis.
3) Difficulty in estimating the risk of MS for non-MS subjects.
4) Difficulty in managing the temporal change of the status of MS risk factors.

Therefore, it is necessary to develop a method to resolve the shortcomings of the current MS diagnostic criteria.

A. Related Work

Radar charts consist of a set of performance indicators which are set in a circle. The indicators are typically standardized from zero to one, one indicating the highest possible performance. The performance degrees of all indicators are used to construct a plot for the whole system. The quality of the radar charts depends on the validity, reliability, and comprehensiveness of the performance indicators. It is known that radar charts have two important advantages, namely, self-evident visualization and overall performance measurement [19]. Due to these advantages, radar charts are popularly used to assess the performance of various evaluation objectives and to present visual comparison of performance in various fields, such as business management, computer networks, social science and so on [19]–[22]. However, radar charts have rarely appeared in biomedical engineering and healthcare literature. Several precursors have shown the usefulness of radar charts to convey healthcare data to audiences [23], to assess various healthcare technologies [24], or to evaluate the general symptoms in fibromyalgia patients and the intensity scales for pain in critically ill-patients [25], [26]. In the disease diagnosis and management field, there have been several studies for developing personalized disease diagnosis methods to identify and quantify patients' health status, particularly in relation to chronic diseases [27]–[29]. Among them, Jeong and Youn [28] proposed a patient status classification method to quantify the chronic disease status of patients by using patient tier classification and radar chart priority calculation [30], which showed the applicability of the radar chart method in preliminary diagnosis of chronic disease.

As we surveyed in this section, the radar chart is an increasingly popular method used in not only general engineering fields, but also healthcare and biomedical engineering fields. Although the radar chart method is a very effective means of identifying the characteristics of various data including biomed-

ical and healthcare fields, it is known that the method has the following weaknesses [19].

1) Equally weighted indicators which are problematic and unjustified.
2) No explanation for status levels and changes of status.
3) No information about risk quantification by comparing measurement results with reference criteria.

There have been several previous studies to improve shortcomings of the traditional radar chart method. The improvement typically has been achieved through transforming a radar chart into an improved radar chart by using linear, nonlinear, or a polar-coordinates-based transformation [31], [32]. According to the literature survey, the previous work has been mainly focused on improving the traditional radar chart to allow different weights on the indicators. However, to apply the radar chart method to risk quantification of MS diagnostic criteria, other limitations of the traditional radar chart should be resolved.

Therefore, to resolve the shortcomings of MS diagnosis methods discussed earlier through the radar chart methodology, this paper first proposes a new weighted radar chart construction method which extends the conventional radar chart-based chronic disease classification method to quantitatively describe the status of MS risk factors. Then, it presents a novel MS risk quantification model that is based on the similarity analysis between the proposed weighted radar charts consisting of MS diagnostic criteria and the examination results of MS risk factors of a subject. In the following sections, a description of the proposed model for quantifying MS risk of a subject is presented, along with its related weighted radar chart construction procedures. Furthermore, the effectiveness of the proposed model is extensively evaluated using data from the third Korea National Health and Nutrition Examination Survey (KNHANES III) [33] while emphasizing the capability to identify potential MS patients. Finally, the discussion and open issues are presented.

II. Novel MS Risk Quantification Model

A. Construction of Weighted Radar Chart for Describing the Status of MS Risk Factors

As we discussed in the previous section, the radar chart is a very useful method for qualitative data analysis despite its weaknesses, and it is useful for preliminary identification of a patient's chronic disease and disease status [28]. Therefore, to mitigate the weaknesses of the radar chart, we have adopted the analytic hierarchy process (AHP) in determining the different weights of MS risk factors. Also, we propose a method for constructing a weighted radar chart. The AHP is a well-known multicriteria decision making method developed by Saaty [34], which allows decision makers to model a complex problem in a hierarchical structure, investigating the relative importance of components comprising the problem. To determine the weights of each risk factor of MS by using the AHP, we first decompose the problem, in which the risk factors should be determined, into a hierarchy of more easily comprehended subproblems and obtain the relative importance between each risk factor by pairwise comparison. The weights can be computed by constructing a pairwise comparison matrix and checking the consistency.

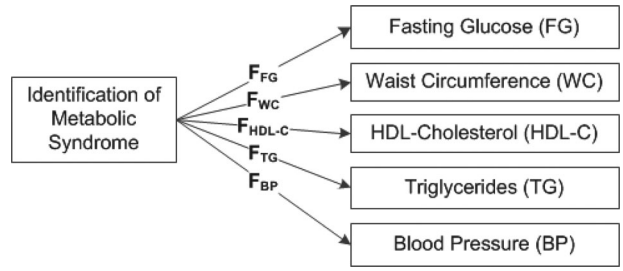

Fig. 1. Decomposition of risk factor structure for MS.

Thus, we apply the AHP to determine the weights of each risk factor of MS.

Many variables are put into the same coordinate plane, the area is the representation function for the whole quality, and the shape gives the detail characteristics. In the weighted radar chart, every input variable value is expressed by radial r_i of a unit circle, and w_i is the weight coefficient. The unit circle could be divided into n parts according to different weight coefficients w_i and the sum of the w_i coefficients is equal to 1. On the circle, the n rays represent the n input variables, and the r_i measures value of an input variable that falls in a relevant ray. By connecting the points r_i, a weighted radar chart could be obtained. Since input data for each MS risk factor in the weighted radar chart have different measurement scales, the input data are normalized to fit into the new input range from 0 to 1.

Let the result of the ith risk factor be x_i and the maximum and minimum value of input data be $x_{i_{\max}}$ and $x_{i_{\min}}$. Then, $x_{i_{\text{new}}}$, the normalized value of x_i can be written as follows:

$$x_{i_{\text{new}}} = (x_i - x_{i_{\min}})/(x_{i_{\max}} - x_{i_{\min}}). \tag{1}$$

Since each risk factor has a different effect on MS status, it is necessary to separately determine the weight of each risk factor to the disease status. To separately decide the relative weight of the risk factors, we utilized the results of risk factor analysis for MS. Fig. 1 shows the decomposition of the risk factor structure for MS. In this section, we use the following sample prevalence results of each risk factor. A description of how to determine the prevalence of risk factors will be provided in Section III:

$$\begin{aligned}&[F_{\text{FG}}, F_{\text{WC}}, F_{\text{HDL-C}}, F_{\text{TG}}, F_{\text{BP}}]\\ &= [0.281,\ 0.265,\ 0.452,\ 0.381,\ 0.456]\,.\end{aligned} \tag{2}$$

Then, pairwise comparison matrix A for risk factors using the sample prevalence can be setup as follows [34]:

$$A = \begin{array}{c} \begin{array}{ccccc} \text{FG} & \text{WC} & \text{HDL-C} & \text{TG} & \text{BP} \end{array} \\ \begin{bmatrix} 1 & 1.0603 & 0.6217 & 0.7375 & 0.6162 \\ 0.9431 & 1 & 0.5863 & 0.6955 & 0.5811 \\ 1.6085 & 1.7057 & 1 & 1.1864 & 0.9912 \\ 1.3559 & 1.4377 & 0.8429 & 1 & 0.8355 \\ 1.6228 & 1.7208 & 1.0089 & 1.1969 & 1 \end{bmatrix} \end{array} \begin{array}{c} \\ \text{FG} \\ \text{WC} \\ \text{HDL-C} \\ \text{TG} \\ \text{BP} \end{array}$$

where a_{ij} is the relative importance of the ith element in the jth indicator criterion level in terms of its contribution to the disease status, and n is the rank of this matrix. a_{ij} is calculated as a ratio

TABLE II
COMPUTED WEIGHTS FOR EACH INDICATOR AND ALLOCATION OF ANGLE IN RADAR CHART

Examination Test Type	Weight (%)	Allocation of Angle (Weight(%)*360°) (°)
Fasting Glucose (FG)	15.31	55.1
Waist Circumference (WC)	14.44	52.0
HDL-Cholesterol (HDL-C)	24.63	88.7
Triglycerides (TG)	20.76	74.7
Blood Pressure (BP)	24.85	89.5

of F_i to F_j listed in (2). Once the pairwise comparison matrix has been established, the weight of each element being compared can be calculated. In this paper, we have used the logarithmic least-squares method to obtain the weights. The relative weight vector W can be obtained by solving the following equations [34]:

$$\min \sum_{i=1}^{n}\sum_{j=1}^{n}\left(a_{ij}-\frac{w_i}{w_j}\right)^2 \tag{3}$$

$$\sum_{i=1}^{n} w_i = 1, \quad w_i > 0 \quad \text{for } i = 1, \ldots, n. \tag{4}$$

Obtained vector W for the relative weights of risk factors is given as follows:

$$\begin{aligned} W &= [\text{FG, WC, HDL} - \text{C, TG, BP}] \\ &= [0.1531,\ 0.1444,\ 0.2463,\ 0.2076,\ 0.2485]\,. \end{aligned} \tag{5}$$

The computed weights and allocation of angle for MS risk factors are shown in Table II.

The circle of the weighted radar chart is marked off in accordance with the number of risk factors and the weights calculated above. Some radial lines are formed by the center of the circle and the marked point. These lines are regarded as coordinate axes. We pretreat the data on these coordinate axes and connect the marked points. Then, polygons for the values of risk factors can be obtained. This is the weighted radar chart of MS risk factors status for a subject. Fig. 2 depicts a weighted radar chart using a sample subject's examination results shown in Table III [35]. The normalization of examination results is performed by using (1), and the maximum and minimum values of each risk factor are imported from the investigated results in [33]. Among the risk factors, the status of HDL-cholesterol becomes worse as the value decreases. Thus, the result of HDL-cholesterol is normalized as follows:

$$x_{\text{HDL-C}_{\text{new}}} = 1 - \frac{(x_{\text{HDL-C}} - x_{\text{HDL-C}_{\min}})}{(x_{\text{HDL-C}_{\max}} - x_{\text{HDL-C}_{\min}})}. \tag{6}$$

B. MS Risk Quantification Model Using Areal Similarity Degree (ASD) Analysis

As we discussed in Section I, the current diagnostic criteria of MS have the following weaknesses.

1) Variation in the importance of risk factors on the development of CVD and T2DM is not considered.

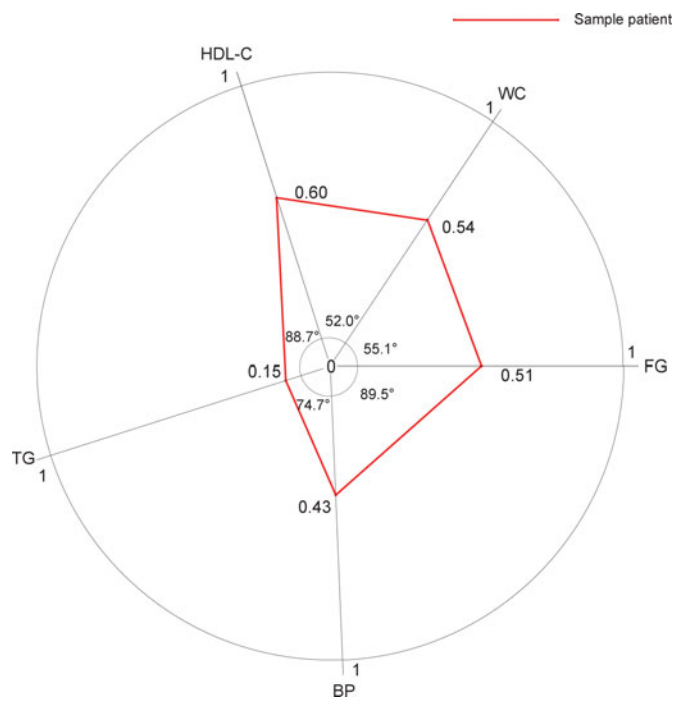

Fig. 2. Weighted radar chart for status of MS risk factors.

TABLE III
SAMPLE EXAMINATION RESULTS OF TYPE 2 DIABETES PATIENT (MALE)

Examination Test Type	Sample Patient	Max	Min
Fasting Glucose (FG) (mg/dl)	176	295	51
Waist Circumference (WC) (cm)	88	127	43
HDL-Cholesterol (HDL-C) (mg/dl)	50	103	15
Triglycerides (TG) (mg/dl)	164	929	31
Blood Pressure (SBP/DBP) (mmHg)	125/80	203/140	70/35

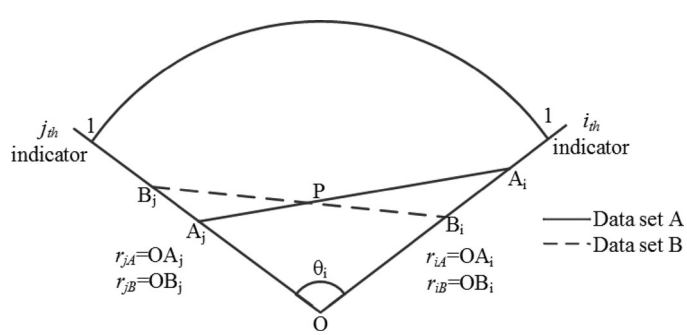

Fig. 3. Partial radar chart consisting of two polygons.

2) Diagnosis is based on the number of risk factors exceeding the thresholds of each, so it is difficult to estimate the risk of MS for a person who is diagnosed as not having MS.
3) It is difficult to manage the progressive process over time.

Therefore, in this section, we propose an MS risk quantification model utilizing the comparison result of two weighted radar charts constructed using MS diagnostic criteria and the examination results of a subject, respectively. The comparison is performed based on the ASD analysis defined in this section.

Let us consider a partial radar chart consisting of two polygons A_{ij} and B_{ij} depicted in Fig. 3.

Definition 1: Let radar chart R be a set of disjoint polygons A_{ij}, where $i = 1, \ldots, n$ and $j = (i+1) \bmod n$.

Definition 2: Let polygon A_{ij} in radar chart R be a polygon consisting of vertices O, A_i, and A_j, i.e., triangle ΔOA_iA_j, where $\overline{OA_i} = r_{i_A}, \overline{OA_j} = r_{j_A}, \angle O = \theta_i, i = 1, \ldots, n, j = (i+1) \bmod n$, and r_i is the value of the ith indicator.

Definition 3: Let the ASD of two polygons A_{ij} and B_{ij} be the ratio of the intersection area of the two polygons A_{ij} and B_{ij} over the area of polygon B_{ij}. In other words, the ASD of two polygons

$$S(A_{ij}|B_{ij}) = \frac{\text{Area of intersection of polygon } A_{ij} \text{ and } B_{ij}}{\text{Area of polygon } B_{ij}}. \tag{7}$$

In (7), polygon B_{ij} is used for the reference polygon determined by the thresholds of MS risk factors and polygon A_{ij} is determined by the examination results of the risk factors for an individual. Thus, (7) describes how the individual's examination results of the risk factors are close to the thresholds of MS risk factors.

Definition 4: Given two polygons A_{ij} and B_{ij}, let polygon A_{ij} include polygon B_{ij}, iff $r_{i_A} \geq r_{i_B}$ and $r_{j_A} \geq r_{j_B}$.

Theorem 1: Given two indicators i and j, the ASD of two polygons A_{ij} and B_{ij}, namely, $S(A_{ij}|B_{ij})$ can be calculated as follows:

$$S(A_{ij}|B_{ij}) = \begin{cases} 1, & \text{if } A_{ij} \text{ includes } B_{ij} \\ \dfrac{\text{Area of } A_{ij}}{\text{Area of } B_{ij}}, & \text{if } B_{ij} \text{ includes } A_{ij} \\ \dfrac{r_{j_B} \cdot r_{i_B} - Q}{r_{j_B} \cdot r_{i_B}}, \text{ where } Q = \dfrac{r_{i_A} \cdot r_{i_B} (r_{j_B} - r_{j_A})^2}{r_{j_A}(r_{i_A} - r_{i_B}) + r_{i_A}(r_{j_B} - r_{j_A})}, & \\ & \text{if } r_{i_A} > r_{i_B} \text{ and } r_{j_A} < r_{j_B} \\ \dfrac{r_{j_B} \cdot r_{i_B} - Q'}{r_{j_B} \cdot r_{i_B}}, \text{ where } Q' = \dfrac{r_{j_A} \cdot r_{j_B} (r_{i_B} - r_{i_A})^2}{r_{i_A}(r_{j_A} - r_{j_B}) + r_{j_A}(r_{i_B} - r_{i_A})}, & \\ & \text{if } r_{i_A} < r_{i_B} \text{ and } r_{j_A} > r_{j_B} \end{cases} \tag{8}$$

Proof:

1) According to Definition 4, when A_{ij} includes B_{ij}, the intersection of the two polygons is B_{ij}. Therefore, $S(A_{ij}|B_{ij})$ is 1.
2) When B_{ij} includes A_{ij}, the intersection of the two polygons is A_{ij}. Therefore, $S(A_{ij}|B_{ij})$ is Area of A_{ij}/ Area of B_{ij}.
3) In Fig. 3, let $\angle B_j = \alpha$. Then, by applying the law of sines and Menelaus' theorem [36] as well as a few algebraic calculations, we can obtain

$$PB_i = \frac{r_{j_A}(r_{i_A} - r_{i_B}) \cdot PB_j}{r_{i_A}(r_{j_B} - r_{j_A})}. \tag{9}$$

Since $B_iB_j = PB_i + PB_j$, the area of ΔA_jB_jP in Fig. 3 becomes

$$\Delta A_jB_jP = \frac{r_{i_A} \cdot r_{i_B}(r_{j_B} - r_{j_A})^2}{2\{r_{j_A}(r_{i_A} - r_{i_B}) + r_{i_A}(r_{j_B} - r_{j_A})\}}. \tag{10}$$

Let the area of ΔOB_jB_i be U, and let the area of $\square OB_iPA_j$ be T. Then, according to Definition 3, $S(A_{ij}|B_{ij})$ becomes $\frac{T}{U}$, and we obtain

$$S(A_{ij}|B_{ij}) = \frac{T}{U} = \frac{r_{j_B} \cdot r_{i_B} - Q}{r_{j_B} \cdot r_{i_B}}, \text{ where}$$
$$Q = \frac{r_{i_A} \cdot r_{i_B}(r_{j_B} - r_{j_A})^2}{r_{j_A}(r_{i_A} - r_{i_B}) + r_{i_A}(r_{j_B} - r_{j_A})}. \tag{11}$$

4) Let $\angle B_i = \alpha$ and in a similar way to case 3, we can obtain $S(A_{ij}|B_{ij})$ for case 4 as follows:

$$S(A_{ij}|B_{ij}) = \frac{r_{j_B} \cdot r_{i_B} - Q'}{r_{j_B} \cdot r_{i_B}}, \text{ where}$$
$$Q' = \frac{r_{j_A} \cdot r_{j_B}(r_{i_B} - r_{i_A})^2}{r_{i_A}(r_{j_A} - r_{j_B}) + r_{j_A}(r_{i_B} - r_{i_A})}. \tag{12}$$

q.e.d.

Since current MS diagnosis methods judge the presence of MS only by checking whether the examination results of each risk factor exceed thresholds of the risk factors, it is not possible to provide any information when the examination results do not exceed the thresholds. Thus, when the examination results are within the thresholds of risk factors, the risk for a subject may be decided by the physician's knowledge. The ASD defined in Theorem 1 shows the overall achievement of examination results of a subject versus thresholds of MS risk factors. Let us assume that, in Fig. 3, the ith indicator and the jth indicator are two risk factors of MS, and data set A (solid line) and data set B (dashed line) are the examination results and thresholds of the two risk factors, respectively. When data set A includes data set B, we can decide that both examination results exceed the thresholds. When either one or none of the examination results exceed a threshold, the intersection between polygons consisting of thresholds and examination results is calculated and is used to express the achievement for each risk factor, respectively. Thus, we can quantify the risk for those two risk factors by using the intersection.

Definition 5: Let the ASD of two radar charts R_1 and R_2 be the ratio of the intersection area of the two radar charts, R_1 and R_2, over the area of radar chart R_2. In other words, the ASD of two radar charts

$$S(R_1|R_2) = \frac{\text{Area of intersection of radar charts } R_1 \text{ and } R_2}{\text{Area of radar chart } R_2}.$$

Theorem 2: Let the ASD of two radar charts R_A and R_B be $S(R_A|R_B)$. Then, $S(R_A|R_B)$ is the weighted sum of $S(A_{ij}|B_{ij})$, where w_i is a weight of A_{ij} and B_{ij}, and $i = 1, \ldots, n$ and $j = (i+1) \bmod n$, and $w_i = \frac{\theta_i}{360}$.

In other words, $S(R_A|R_B) = \sum_{i=1}^{n} \frac{\theta_i}{360} \cdot S(A_{ij}|B_{ij})$, where $\sum_i^n \theta_i = 360, j = (i+1) \bmod n$.

TABLE IV
THRESHOLDS OF FIVE RISK FACTORS OF MS FOR KOREAN SUBJECTS

Examination Test Type	Thresholds
Fasting Glucose (FG) (mg/dl)	≥ 100mg/dl
Waist Circumference (WC) (cm)	≥ 90 (for male) ≥ 85 (for female)
HDL-Cholesterol (HDL-C) (mg/dl)	< 40 (for male) < 50 (for female)
Triglycerides (TG) (mg/dl)	≥ 150mg/dl
Blood Pressure (BP) (mmHg)	≥ 130/85mmHg

Proof: Since a radar chart comprises n disjoint parts, the areal similarity of two radar charts can be calculated by adding the weighted ASDs of n disjoint parts.

According to Definition 3, we can obtain the following:

$$S(A_{12}|B_{12}) = \frac{A_{12} \cap B_{12}}{B_{12}}, \ldots, S(A_{n1}|B_{n1}) = \frac{A_{n1} \cap B_{n1}}{B_{n1}}. \tag{13}$$

Also, the weights of A_{12} and B_{12} are calculated as follows:

$$\begin{aligned} \text{weight of } A_{12} = \text{ weight of } B_{12} = w_1 &= \frac{\theta_1}{360} \\ &= \frac{B_{12}}{\sum_{i,j} B_{ij}} = \frac{A_{12}}{\sum_{i,j} A_{ij}} \end{aligned} \tag{14}$$

$$\begin{aligned} \text{weight of } A_{n1} = \text{ weight of } B_{n1} = w_n &= \frac{\theta_n}{360} \\ &= \frac{B_{n1}}{\sum_{i,j} B_{ij}} = \frac{A_{n1}}{\sum_{i,j} A_{ij}}. \end{aligned} \tag{15}$$

According to Definition 3, Definition 5, and (13)–(15)

$$\begin{aligned} S(R_A|R_B) &= \frac{S(A_{12}|B_{12}) \cdot B_{12}}{\sum_{ij} B_{ij}} + \cdots + \frac{S(A_{n1}|B_{n1}) \cdot B_{n1}}{\sum_{ij} B_{ij}} \\ &= S(A_{12}|B_{12}) \cdot w_1 + \cdots + S(A_{n1}|B_{n1}) \cdot w_n \\ &= \sum_{ij} S(A_{ij}|B_{ij}) \cdot w_i. \end{aligned} \tag{16}$$

q.e.d.

As shown in Theorem 2, since a weighted radar chart can be divided into polygons constructed by MS risk factors, we can calculate the overall ASD by combining the ASDs of each polygon. Thus, we can quantify the risk for all of the risk factors by using the sum of intersections.

In this paper, we use the diagnostic criteria defined by NCEP ATP III in 2001 [37]. Among the criteria, we have adopted the waist circumference cut-off value for Korean subjects that was proposed by the Korean Medical Association [38] and the fasting glucose cut-off value that was proposed by the American Diabetes Association [39]. The thresholds of five risk factors for Korean subjects are listed in Table IV.

A subject is determined to have MS, if three or more of the subject's medical examination results exceed the thresholds of risk factors in Table IV. Thus, by comparing the weighted radar chart of the subject with the weighted radar chart of thresholds of risk factors, it is possible to effectively determine whether the subject has MS. Furthermore, by calculating ASD between two weighted radar charts, we can determine whether the subject can be classified into a potential risk group for having MS in the future.

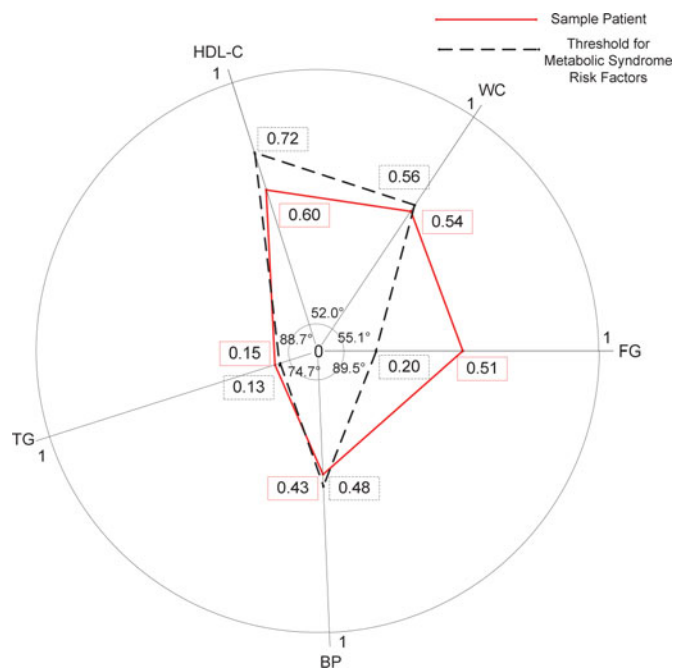

Fig. 4. Two weighted radar charts constructed by examination results of a subject and thresholds of MS risk factors.

Fig. 4 shows the two weighted radar charts for the subject and MS thresholds. Examination results in Table III have been used to construct the weighted radar charts. According to the examination results, the subject is determined not to have MS because only two examination results (fasting glucose and triglycerides) exceed the thresholds. However, the subject has T2DM, and the examination result of triglycerides also indicates the need for caution. Using conventional MS diagnostic criteria, it is difficult to estimate the risk of this kind of subject. We can compute the ASD of this subject as 0.93 based on Theorem 2. The clinical value of the proposed risk quantification model based on ASD will be evaluated and discussed in Section III.

C. Discussion

Since the proposed method is based on the calculation of the ASD of two weighted radar charts that comprise five polygons each, the shapes of the polygons can change as the order that the MS risk factors are arranged within the weighted radar charts changes. Further, these changes may cause changes in the calculated ASD results. This section investigates the effects of changing the order of risk factors to the results. Let us consider the following property of the weighted radar chart.

Property 1: The *ASD* of two polygons A_{ij} and B_{ij} has a symmetric property. Let A_{ij} and B_{ij} be triangles comprising the ordered vertices O, A_i, and A_j and O, B_i, and B_j, respectively. Let A_{ji} and B_{ji} be triangles comprising the ordered vertices O, A_j, and A_i and O, B_j, and B_i, respectively. Then, $S(A_{ij}|B_{ij}) = S(A_{ji}|\mathrm{B}_{ji})$.

Proof: According to Definition 3 and Fig. 3, it is obvious that the following equation holds:

$$\begin{aligned} S(A_{ij}|B_{ij}) &= \frac{\text{Area of intersection of } A_{ij} \text{ and } B_{ij}}{\text{Area of } B_{ij}} \\ &= \frac{\text{Area of intersection of } A_{ji} \text{ and } B_{ji}}{\text{Area of } B_{ji}}. \\ &= S(A_{ji}|B_{ji}) \end{aligned}$$

q.e.d.

Using the property, we can develop the following corollary.

Corollary 1: Let us consider two weighted radar charts with five indicators as shown in Fig. 5 (left). According to Theorem 2, the ASD of radar charts A and B is represented as follows:

$$\begin{aligned} S(R_A|R_B) &= w_1 \cdot S(A_{12}|B_{12}) + w_2 \cdot S(A_{23}|B_{23}) \\ &\quad + w_3 \cdot S(A_{34}|B_{34}) + w_4 \cdot S(A_{45}|B_{45}) + w_5 \cdot S(A_{51}|B_{51}). \end{aligned} \tag{17}$$

Let us assume that we change the order of indicators by interchanging the position of indicators. For simple analysis, we consider exchanging the position of indicator 1 with another indicator. Then, there are two cases.

1) Exchange With an Adjacent Indicator: Let us assume that we exchange indicator 1's position with indicator 2's position as shown in Fig. 5 (middle). Then, the ASD of the modified weighted radar chart is represented as follows:

$$\begin{aligned} S(R'_A|R'_B) &= w_2 \cdot S(A_{21}|B_{21}) + w_1 \cdot S(A_{13}|B_{13}) \\ &\quad + w_3 \cdot S(A_{34}|B_{34}) + w_4 \cdot S(A_{45}|B_{45}) + w_5 \cdot S(A_{52}|B_{52}). \end{aligned}$$

By applying Property 1, the ASD difference of $S(R'_A|R'_B)$ and $S(R_A|R_B)$ becomes

$$\begin{aligned} &\text{Diff of } S(R'_A|R'_B) \text{ and } S(R_A|R_B) = S(R'_A|R'_B) - S(R_A|R_B) \\ &= (w_2 - w_1) \cdot S(A_{12}|B_{12}) + w_5 \cdot \{S(A_{52}|B_{52}) - S(A_{51}|B_{51})\} \\ &\quad + w_1 \cdot S(A_{13}|B_{13}) - w_2 \cdot S(A_{23}|B_{23}). \end{aligned} \tag{18}$$

2) Exchange With a Nonadjacent Indicator: Let us assume that we exchange indicator 1's position with indicator 3's position as shown in Fig. 5 (right). Then, the ASD of the modified weighted radar chart is expressed as follows:

$$\begin{aligned} S(R''_A|R''_B) &= w_3 \cdot S(A_{32}|B_{32}) + w_2 \cdot S(A_{21}|B_{21}) \\ &\quad + w_1 \cdot S(A_{14}|B_{14}) + w_4 \cdot S(A_{45}|B_{45}) + w_5 \cdot S(A_{53}|B_{53}). \end{aligned}$$

The ASD difference of $S(R''_A|R''_B)$ and $S(R_A|R_B)$ becomes

$$\begin{aligned} &\text{Diff of } S(R''_A|R''_B) \text{ and } S(R_A|R_B) = S(R''_A|R''_B) - S(R_A|R_B) \\ &= (w_3 - w_2) \cdot S(A_{23}|B_{23}) + (w_2 - w_1) \\ &\quad \cdot S(A_{12}|B_{12}) + w_5 \cdot \{S(A_{53}|B_{53}) \\ &\quad - S(A_{51}|B_{51})\} + w_1 \cdot S(A_{14}|B_{14}) - w_3 \cdot S(A_{34}|B_{34}). \end{aligned} \tag{19}$$

Therefore, by using Corollary 1, it is possible to calculate the changed ASD value, when the order of the risk factors is changed. For instance, the ASD of the weighted radar charts in Fig. 4 is calculated as 0.93. If the position of the FG risk factor is moved between HDL-C and TG, the changed ASD value is calculated as 0.92. The effects of changing the order of risk factors to the ASD analyses will be further investigated in the discussion part of Section III.

TABLE V
CHARACTERISTICS OF STUDY SUBJECTS

	Male		Female	
No. of subjects, n (%)	2,276 (42.53)		3,079 (57.47)	
Age, years 20-39 (young) 40-64 (middle-aged) 65+ (old)	47.22±14.61 760 (33.39) 1170 (51.41) 346 (15.20)		46.99±15.62 1118 (36.31) 1449 (47.06) 512 (16.63)	
BMI (kg/m^2)	23.99±3.10	Mn 14.76 Mx 43.39	23.52±3.38	Mn 15.03 Mx 43.79
Fasting glucose (mg/dl)	97.61±22.97	Mn 51.0 Mx 295.0	93.06±19.78	Mn 60.0 Mx 331.0
Waist circumference (cm)	84.30±8.74	Mn 39.0 Mx 133.5	78.46±9.54	Mn 41.5 Mx 118.5
HDL-cholesterol (mg/dl)	42.44±10.15	Mn 15.0 Mx 103.0	47.10±10.88	Mn 18.0 Mx 122.0
Triglycerides (mg/dl)	156.08±110.81	Mn 31.0 Mx 929.0	114.71±75.23	Mn 29.0 Mx 891.0
Systolic BP (mm Hg)	122.82±16.06	Mn 70.0 Mx 203.0	116.44±18.50	Mn 73.0 Mx 219.0
Diastolic BP (mm Hg)	80.74±10.37	Mn 35.0 Mx 140.0	74.72±10.26	Mn 38.0 Mx 133.0
Diabetes mellitus[1], n (%)	157 (6.90)		138 (4.48)	
Hypertension[2], n (%)	523 (22.98)		452 (14.68)	

BMI, body mass index; BP, blood pressure
Values are means ± SD or n (%); Mn, Minimum; Mx, Maximum
[1]Fasting glucose ≥126 mg/dl and/or physician-diagnosed diabetes mellitus
[2]Systolic BP ≥140 mm Hg and/or diastolic BP ≥90 mm Hg and/or physician-diagnosed hypertension

III. EVALUATION AND DISCUSSION

A. Characteristics of Study Subjects

This paper is based on data obtained from the KNHANES III among noninstitutionalized civilians in the Republic of Korea, which was conducted by the Korean Ministry of Health and Welfare in 2005. This survey was a nationwide representative study using a stratified, multistage probability sampling design for the selection of household units [33]. A total of 34 145 individuals from these sampling frames were included in the health interview survey; among them, 25 161 subjects aged over 20 years were identified as potential participants in our study. We excluded those with incomplete data for the standardized analysis. This resulted in a final analytical sample of 5355 subjects (2276 males, 3079 females), aged over 20 years.

The characteristics of the study population, as stratified by gender, are presented in Table V. In this paper, we have classified total subjects into two subject groups by gender and further classified each subject group into three subgroups by age: young (from 20 to 39 years old), middle-aged (from 40 to 64 years old), and old (more than 65 years old), respectively. Therefore, we use a total of six subgroups for the evaluation of our proposed risk quantification model.

First of all, to analyze the relative weights of MS risk factors among each subgroup, we use prevalence-based weight determination for each MS risk factor for each subgroup [33]. For

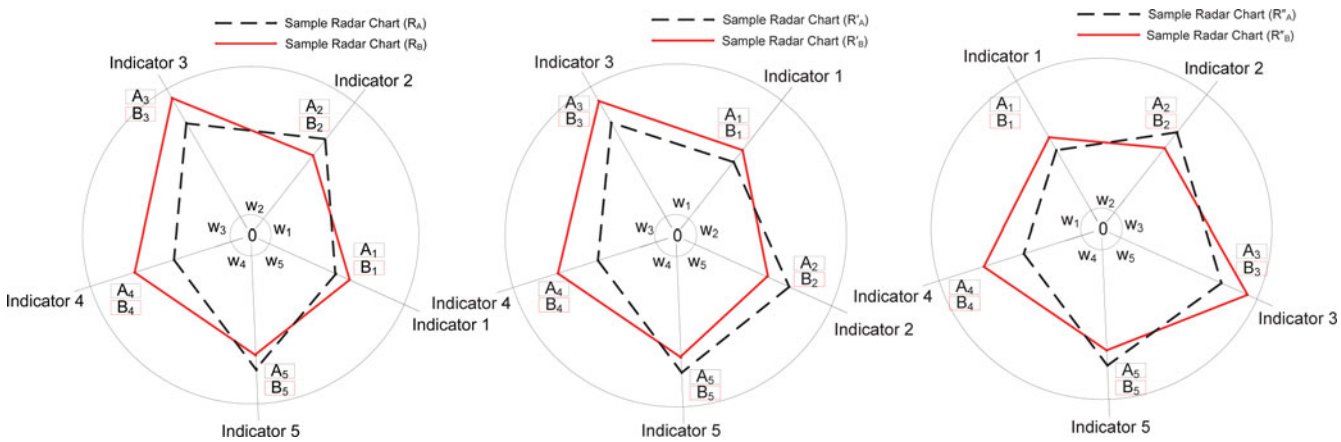

Fig. 5. Weighted radar charts for the order of indicators analysis. (1) (left) Sample weighted radar charts. (2) (middle) Exchange the positions of indicators 1 and 2. (3) (right) Exchange the positions of indicators 1 and 3.

TABLE VI
CALCULATION OF WEIGHTS FOR MS RISK FACTORS AMONG STUDY SUBJECTS

	FG	WC	HDL-C	TG	BP
Male					
Young	0.103	0.199	0.254	0.254	0.190
Middle-aged	0.177	0.174	0.210	0.225	0.214
Old	0.206	0.183	0.206	0.181	0.224
Total	0.168	0.180	0.218	0.222	0.211
Female					
Young	0.159	0.231	0.297	0.203	0.110
Middle-aged	0.156	0.210	0.265	0.182	0.187
Old	0.154	0.200	0.266	0.159	0.221
Total	0.155	0.208	0.268	0.175	0.194

each subgroup, we counted the occurrence of examination results that exceeded the thresholds of each risk factor. Then, the number of occurrence of each risk factor was mapped into the prevalence result of each risk factor in (2). It is noted that how the weight for BP is calculated because there exist two separate components and the corresponding thresholds for systolic blood pressure (SBP) and diastolic blood pressure (DBP). Current MS definitions except IDF have ambiguity on the criteria for BP. For example, it is not clearly described that "BP $\geq$ 130/85 mmHg" implies whether both SBP and DBP need to exceed the corresponding thresholds or either one of the components may need to exceed the thresholds in NCEP ATP III definition [3]. Thus, we used IDF criteria for BP. We separately calculated the prevalence results of SBP and DBP. Then, the larger one is selected as the prevalence of BP. The values of SBP and DBP are separately normalized by using (1). The larger one is selected as the normalized value of BP.

Table VI shows the computed relative weights among MS risk factors. According to the analysis, the prevalence of lipid-related risk factors showed high occurrence, whereas fasting glucose and waist circumference showed relatively low occurrence in male subjects. For female subjects, HDL-cholesterol and waist circumference were identified as major risk factors, whereas triglycerides, which had the highest prevalence for male subjects, was not a major factor.

B. Evaluation

This section presents the evaluation results of the proposed MS risk quantification model obtained using six subgroups. Fig. 6 shows the regression analysis results of the average ASD values of each subgroup according to the number of MS risk factors exceeding the thresholds of each risk factor. According to the analyzed *R-squared* values, we can judge that there is strong positive correlation between the ASD values and the number of MS risk factors. Therefore, we can claim that the proposed ASD can effectively represent MS risk.

Since the proposed risk quantification model is based on ASD values, it is important to determine clinically evaluated thresholds. Thus, we computed the ASD values of each subgroup using the weights for MS risk factors for the subgroups presented in Table VI. Then, we counted the occurrence over ASD values. In this paper, the interval of ASD value is set to 0.01. Fig. 7 shows the analysis results of the number of MS subjects and non-MS subjects over ASD values among male subgroups. The blue line (dashed line) shows the counts of non-MS subjects over ASD value, whereas the green line (solid line) shows the counts of MS subjects. The analysis results indicate that the number of MS-present subjects increases as the ASD value increases, which confirms the positive correlation between ASD values and the risk of having MS. Similar to the results of male subgroups, the analysis results of the female subgroups also have indicated the correlation between ASD values and the risk of having MS in female subjects.

To perform in-depth analysis regarding the determination of ASD thresholds, we further divided each subgroup into four cases, as listed in Table VII. Among the four cases, Cases 2 and 3 indicate the errors of our proposed model. Since Case 3 subjects are already diagnosed to have MS, we focus on identifying Case 2 subjects when determining ASD thresholds. Furthermore, MS is a chronic disease and requires continuous management, so it is more important to identify potential patients that have high risk for having MS in the future rather than accurate diagnosis. Therefore, we determined the ASD threshold for a subgroup as a lower value of ASD where 50% or more of the subjects are identified as having MS.

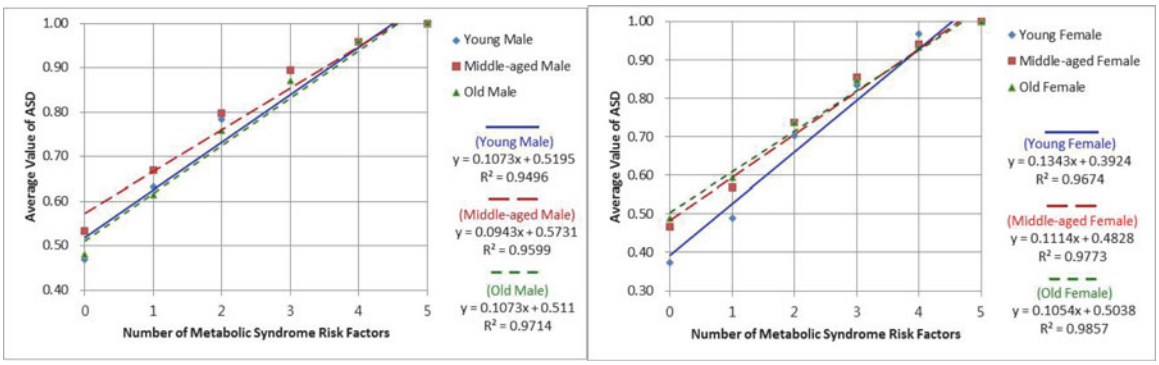

Fig. 6. Regression analysis of proposed ASD-based model and the number of MS risk factors for (left) male subjects subgroups and (right) female subjects subgroups.

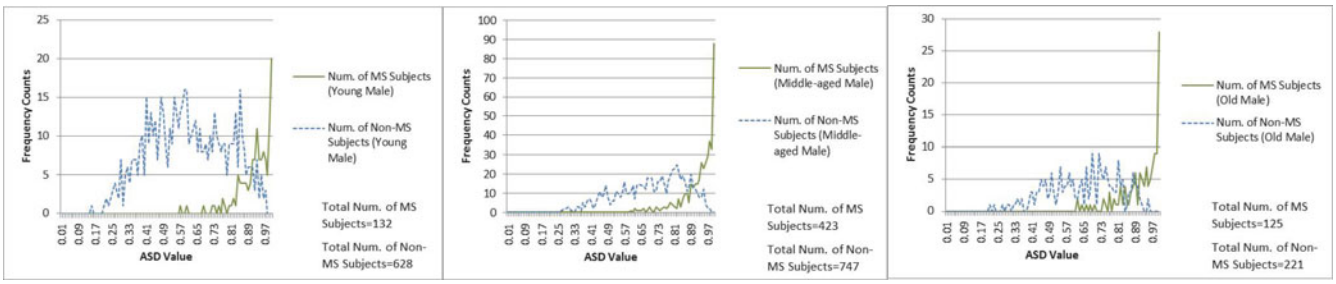

Fig. 7. Analysis of the numbers of MS subjects and non-MS subjects over ASD value for male subgroups: (left) young, (middle) middle-aged, and (right) old. Interval of ASD range = 0.01.

TABLE VII
DETAILED SUBCASES OF EACH SUBGROUP BELONGS TO MALE SUBJECTS

Case 1	A subject whose ASD value exceeds ASD threshold and having MS
Case 2	A subject whose ASD value exceeds ASD threshold and NOT having MS
Case 3	A subject whose ASD value does NOT exceed ASD threshold and having MS
Case 4	A subject whose ASD value does NOT exceed ASD threshold and NOT having MS

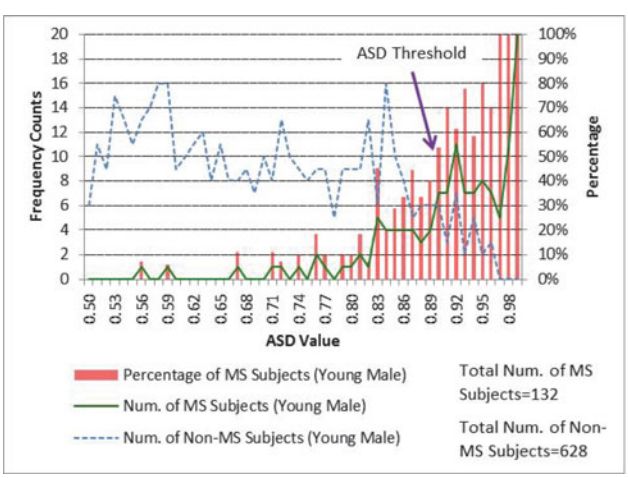

Fig. 8. Detailed analysis of the numbers of MS subjects and non-MS subjects over ASD value for young-male subgroup.

Fig. 8 shows in-depth analysis of the numbers of MS subjects and non-MS subjects over ASD value for the young-male subgroup. The bar graph in red shows the percentage of MS patients over a given ASD range. According to the analysis result, when the ASD range is from 0.90 to 0.91 ($0.90 \leq \text{ASD} < 0.91$), the MS patients percentage is 54%. Therefore, the ASD threshold for young-male subjects can be determined as 0.90.

Similarly, the middle-aged male subgroup shows an MS patient percentage of 50%, when the ASD range is from 0.89 to 0.90 [see Fig. 9 (left)]. Thus, the ASD threshold for middle-aged male subjects becomes 0.89. For the old male subgroup in Fig. 9 (right), the percentage of MS patients first becomes 50% when the ASD range is from 0.61 to 0.62. However, the number of MS subjects and the number of non-MS subjects are 2 and 2, respectively, and the percentage immediately becomes less than 50% after the ASD range. Thus, we have chosen the ASD threshold as the ASD range from 0.81 to 0.82. Therefore, the ASD threshold for old male subjects is 0.81.

We have analyzed the numbers of MS subjects and non-MS subjects over ASD values for the female subgroups similar to the male subgroups. Fig. 10 shows the analysis results for the young-female subgroup. We determined the ASD threshold to be the ASD range from 0.87 to 0.88 ($0.87 \leq \text{ASD} < 0.88$) where the MS patients percentage is 57%. It is noted that the ASD ranges from 0.83 to 0.84 or from 0.85 to 0.86 are not chosen because the numbers of MS subjects and non-MS subjects are small, and the percentage immediately becomes less than 50% after the ASD ranges. Therefore, we determined the ASD threshold for young-female subjects as 0.87. For the middle-aged subgroup, the analysis results have shown the gradual increase in the percentage of MS subjects after exceeding the ASD value of 0.79, which is a similar trend to the middle-aged male subgroup. We chose the ASD range from 0.85 to 0.86, where the MS subjects

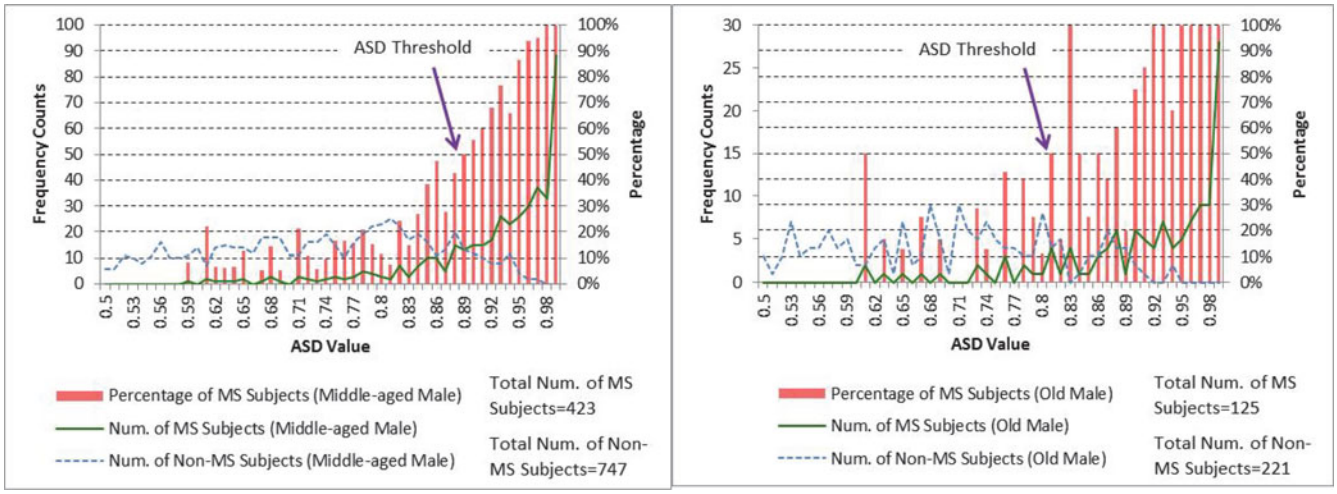

Fig. 9. Detailed analysis of the numbers of MS subjects and non-MS subjects over ASD value for male subgroups: (left) middle-aged and (right) old.

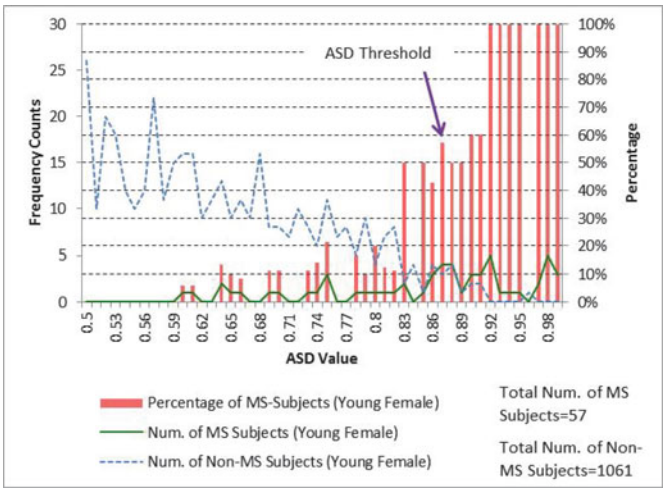

Fig. 10. Detailed analysis of the numbers of MS subjects and non-MS subjects over ASD value for young-female subgroup.

percentage is 62%. Thus, the ASD threshold for middle-aged female subjects becomes 0.85. For the old female subgroup, similar to the old male subgroup, early peaks indicating more than 50% of MS subjects occurred at the ASD ranges from 0.66 to 0.67 or from 0.78 to 0.79. However, the peaks immediately disappeared after the ASD ranges, so those ASD ranges were not selected. We chose the ASD range from 0.82 to 0.83, where the percentage of MS patients is 70%. Therefore, the ASD threshold for the old female subgroup is 0.82.

Table VIII lists the examination results for MS risk factors for Case 2 subjects. According to the analysis results, for young- and middle-aged males, triglycerides is the most frequent risk factor for the prevalence of MS, whereas blood pressure, especially SBP, is the most frequent factor for old males. For females, HDL-cholesterol is the most frequent risk factor for all subgroups. These analysis results imply that the frequent risk factors occurring in ASD ranges where more than 50% of subjects are MS patients are high triglycerides, low HDL-cholesterol, and high SBP. It is noted that young males and females show high DBP results with low numbers of risk factors. The main reason for these results is due to the small sample sizes of these subgroups. Especially, for young-female subgroups having one risk factor, one subject had low HDL-cholesterol value, but the other had hypertension with high SBP and DBP. These caused the high mean and standard deviation of DBP for the young-female subgroup.

C. Discussion

This section discusses several important issues regarding the advantages and disadvantages as well as the applicability of the proposed ASD method.

1) Dependency on the Order of Risk Factors Arranged in the Weighted Radar Chart: As we discussed in Section II, the order of risk factors affects the computed ASD values and the changed ASD values can be calculated based on Corollary 1. In this section, we investigate whether the changes of the order of risk factors affect the ASD analysis results including ASD thresholds and the number of subcases of each subgroup represented by male and female subjects, respectively. According to Table VII, Cases 1 and 3 indicate the subjects diagnosed as MS, whereas Cases 2 and 4 refer to the subjects not having MS. Since the main objective of the ASD method is to screen subjects with a high risk of MS, which is difficult to identify using the conventional diagnosis criteria, we focus on the analysis of changes between Cases 2 and 4.

The ASD analysis results presented in Section III are based on the order of risk factors as shown in Fig. 4 (FG, WC, HDL-C, TG, and BP). To investigate the effects of changing the order, we applied an example of changed order of risk factors as FG, WC, TG, HDL-C, and BP to the ASD analysis. Then, the numbers of subjects who had been in Case 2 and reclassified as Case 4 or vice versa are counted. The changes of ASD thresholds were also computed.

Table IX lists the changes of the relevant numbers. The numbers of subjects who had been classified as Case 2 and were reclassified as Case 4 or vice versa indicate the error of the ASD method. As shown in the table, fewer subjects changed from

TABLE VIII
EXAMINATION RESULTS FOR MS RISK FACTORS FOR CASE 2 SUBJECTS

Sub-groups of Case 2 Subject (ASD threshold)	Number of risk factors (number of subjects)	WC	HDL-C	TG	SBP	DBP	FG
Young male (0.90)	0 (3)	82.4±5.3	44.0±2.2	137.7±7.9	122.0±3.6	83.3±0.5	93.3±3.8
	1 (34)	83.8±4.0	42.1±5.4	179.8±43.8	116.8±6.9	78.7±5.8	93.0±10.4
	2 (79)	85.2±6.2	38.0±7.2	216.9±84.1	119.910.9	79.8±8.5	92.3±8.3
Middle-aged male (0.89)	0 (23)	85.0±3.3	44.0±4.6	128.3±12.8	117.3±6.7	78.3±4.5	91.9±5.8
	1 (130)	83.9±4.5	42.9±8.0	147.9±51.7	119.3±10.8	79.6±6.9	98.1±23.3
	2 (239)	85.9±5.4	40.0±7.6	180.1±89.9	124.4±16.0	83.6±9.9	101.6±28.3
Old male (0.81)	0 (5)	81.1±5.5	44.4±3.7	127.2±18.1	116.0±7.0	73.4±7.9	91.6±5.2
	1 (39)	83.7±7.9	45.6±9.9	127.5±32.3	128.9±14.9	77.6±7.3	93.3±6.9
	2 (72)	86.1±7.1	41.7±9.9	134.7±64.9	135.7±20.2	80.1±11.6	100.7±19.5
Young female (0.87)	0 (0)	0	0	0	0	0	0
	1 (2)	82.1±0.4	44.5±8.5	124.5±4.5	146.0±24	96.5±14.5	95.5±1.5
	2 (16)	83.5±6.7	40.3±7.9	195.1±63.5	110.6±5.4	77.1±4.0	94.3±7.4
Middle-aged female (0.85)	0 (10)	78.5±3.6	53.6±2.2	129.8±13.0	116.0±9.9	75.4±4.4	92.7±3.3
	1 (81)	79.4±5.1	46.5±8.7	135.4±39.0	117.4±11.7	76.7±5.4	91.4±5.0
	2 (225)	81.9±7.0	42.2±8.4	159.2±87.8	121.3±15.6	79.3±9.1	98.5±24.2
Old female (0.82)	0 (19)	75.1±5.9	57.3±4.9	90.6±21.5	118.3±7.7	70.3±7.1	89.0±6.3
	1 (82)	76.7±6.7	49.9±14.5	95.6±30.1	127.3±18.1	77.1±11.1	91.0±7.3
	2 (141)	80.4±8.7	45.0±9.7	119.0±49.1	134.7±19.5	78.2±9.8	97.0±23.1

* Values are means ± SD, standard deviation

TABLE IX
CHANGES IN THE NUMBER OF CASE 2, CASE 4, AND ASD THRESHOLDS

		Num. of Case 2 subjects	Num. of Case 4 subjects	Num. of Case 2 → Case 4, (%)	Num. of Case 4 → Case 2, (%)	ASD_{ORG}	ASD_{NEW}
Male	Young	28	600	0 (0)	10 (1.7)	0.90	0.88
	Mid.	71	676	4 (5.6)	19 (2.8)	0.89	0.88
	Old	35	186	1 (2.9)	5 (2.7)	0.81	0.80
Female	Young	13	1048	1 (7.7)	8 (0.8)	0.87	0.85
	Mid.	63	1015	3 (4.8)	16 (1.6)	0.85	0.83
	Old	35	229	2 (5.0)	7 (3.1)	0.82	0.81

ASD_{ORG}, threshold with the original order; ASD_{NEW}, threshold with the new order

Case 2 to Case 4 than from Case 4 to Case 2. However, the error percentages of Case 2 subjects are greater than those of Case 4 subjects due to the large difference in the numbers of Cases 2 and 4 subjects. Since the ASD values of the subjects change as the order changes, the ASD thresholds also change. In our analysis, the new ASD thresholds became lower than the original ASD thresholds. The decrease of ASD thresholds caused more subjects to change from Case 4 to Case 2 than from Case 2 to Case 4. Case 4 indicates subjects whose ASD values are below ASD thresholds and who are not being diagnosed with MS. Thus, as the ASD thresholds decrease, some subjects in Case 4 may exceed the decreased ASD thresholds. We have performed an investigation on the effects of changing the order of risk factors on the ASD method and showed that the effects are not significant; however, developing a more formal mathematical model to describe and quantify the effects of changing the order of risk factors is required in for further study.

2) Clinical Benefits and Applicability to Other Populations: According to the evaluation results presented in the previous section, when a subject has an ASD value greater than the threshold and is not determined to have MS based on the conventional MS diagnostic criteria, we can estimate that the subject has a more than 50% risk of developing MS. Thus, through the proposed risk quantification model that is based on ASD rather than the conventional MS diagnosis methods relying on the number of risk factors, it is possible to estimate the risk of having MS and systematically manage the important risk factors for CVD and T2DM. By doing this, the model proposed in this paper can contribute to prevention of CVD and T2DM. Also, the proposed risk quantification model that is based on ASD could be applied to the management of other diseases.

Therefore, if a subject whose ASD value exceeds the designated threshold is found to have those MS risk factors, the risk of developing MS, CVD, and T2DM can be reduced by proactive medication and treatment, as well as improvement of living habits.

The proposed model in this paper determines a reference that comprises the weights and ASD thresholds for MS risk quantification using the medical examination results of a large number of sample subjects. Thus, the change of sampling population may cause the changes of the reference comprising the weights and ASD thresholds. For example, when we applied the proposed method to the recent data obtained from the fourth Korea National Health and Nutrition Examination Survey [40], the ASD threshold values were changed, but the correlation between ASD values and having MS risk was retained. Further, assigning different weights on MS risk factors also reduced the errors of the proposed method, similar to KNHANES III database. Therefore, the proposed method is adaptively applicable to various populations and the values of ASD thresholds and weights can be computed in accordance with a target population. It is noted that the determined values of weights and ASD thresholds may need to be updated by using periodic health examination results because the characteristics of the target population may change over time due to various reasons.

The following summarizes the procedures for utilizing the ASD method.

1) At time T_0: Determine a reference values for MS risk factors' weights and ASD thresholds using examination data for a population.
2) After the determination of the reference, use the established reference for predicting MS risk of individuals.
3) At time T_i: Update the reference using new examination data for the population.
4) After the update, use the updated reference for predicting MS risk of individuals.

Furthermore, our proposed method can be applied to other populations, if there exist examination results of MS risk factors for large samples. Currently, the U.S. [41], New Zealand [42], and Australia [43] also provide nationwide health examination results for research and public healthcare purposes. Therefore, our proposed method can be applied to those populations. Further, the report published by the US Center for Disease Control and Prevention (CDC) indicated that Brazil, Kuwait, South Africa, Israel, United Kingdom, and France were also planning national health examination surveys and collaborating with CDC [44], so our proposed method could be applied to those populations in the future.

3) Side Effects and Weaknesses: The method for deciding the weights of MS risk factors used in this paper is based on the frequency of each risk factor in the examination results. Therefore, changes of examination subjects cause changes of weights. The selection of KNHANES III sample subjects was performed with consideration of the statistical characteristics so that the sample subjects would accurately represent the Korean population, but the determination of weights may still be biased, because the examination did not cover the whole Korean population.

Our proposed model quantifies the risk of having MS by using ASD, which is an integrated indicator of MS risk factors. Thus, during the integration procedure based on standardizing the examined values of each risk factor, the originally examined values are integrated with dimensionless values between 0 and 1. This characteristic may cause two subjects having the same ASD value to have different values for each MS risk factor. For example, let us assume that two subjects have the same ASD value of 0.8. Then, it is possible for one subject to have high HDL-C, WC, and TG values and the other subject to have high values of FG, BP, and TG. Thus, it is necessary to draw a weighted radar chart of the subjects' examination results of MS risk factors to investigate the status of the risk factors in detail. Therefore, the ASD model can be utilized as a screening criterion for subjects with potential risk of MS, and the risk of each MS risk factor can be analyzed by using the weighted radar chart.

4) Comparison With Equally Weighted Method: Since the ASD method allows different weights on MS risk factors, the comparison with the conventional equal weights-based method needs to be discussed in order to quantify the benefit of the ASD method. We performed the comparison using the young-male and -female subjects. It is important to screen the subjects with high risk of MS (Case 2), which it is difficult to identify using the current MS diagnosis criteria, so we compared the capability for screening Case 2 subjects by counting the number of Case 2 over ASD value. Fig. 11 shows the differences of the number of Case 2 subjects between the ASD method ($\mathrm{CASE2_{ASD}}$) and the equally weighted radar chart method ($\mathrm{CASE2_{EWR}}$) by subtracting the number of $\mathrm{CASE2_{EWR}}$ from $\mathrm{CASE2_{ASD}}$. As shown in the figure, the conventional equally weighted radar chart method is inferior to identifying Case 2 subjects over ASD values. In the figure, the blue bar and the red bar indicate the ASD thresholds for young-male and -female subjects determined in the previous Section B. By using the number of Case 2 subjects listed in Table IX, we can calculate the accuracy for identifying Case 2 subjects using the equally weighted radar chart method as 46.2% for young-female subjects and 78.6% for young-male subjects, respectively. It is noted that when the ASD value is larger than 0.96, the differences of the number of $\mathrm{CASE2_{EWR}}$ and $\mathrm{CASE2_{ASD}}$ become zero for both male and female subjects. The reason for these is that all subjects whose ASD values are larger than 0.96 are MS diagnosed subjects (see Fig. 8 and Fig. 10).

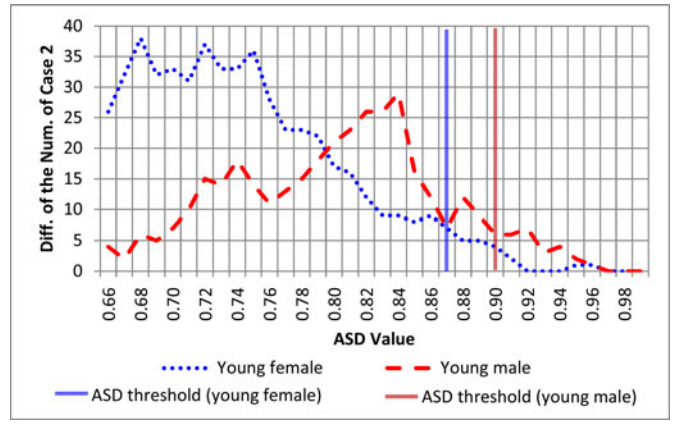

Fig. 11. Differences of the number of Case 2 subjects between $\mathrm{CASE2_{EWR}}$ and $\mathrm{CASE2_{ASD}}$ over ASD value.

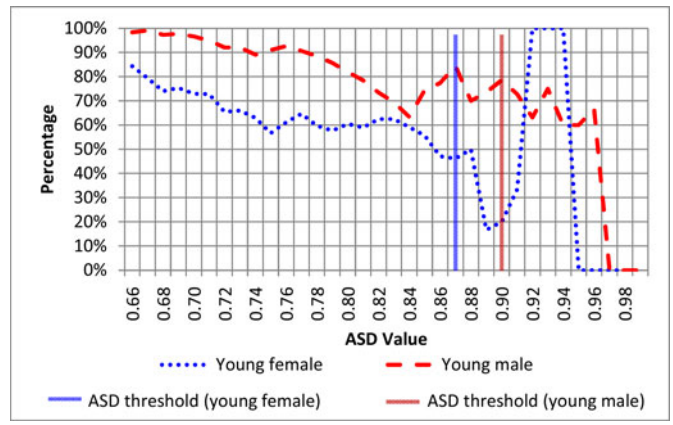

Fig. 12. Ratio of total number of Case 2 subjects of $\mathrm{CASE2_{EWR}}$ to $\mathrm{CASE2_{ASD}}$.

Fig. 12 shows the ratio of total number of Case 2 subjects of $\mathrm{CASE2_{EWR}}$ to $\mathrm{CASE2_{ASD}}$ over ASD value. In accordance

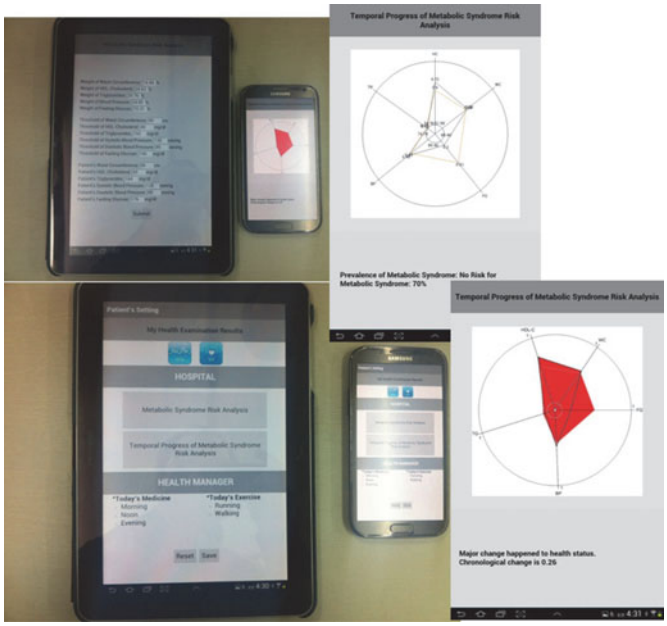

Fig. 13. Prototype implementation of MS risk management application.

with Fig. 11, the numbers of $\mathrm{CASE2}_{\mathrm{EWR}}$ are smaller than those of $\mathrm{CASE2}_{\mathrm{ASD}}$ for both subjects.

5) Applicability to Managing Temporal Changes: Since ASD value can serve as an initial criterion for screening risk of having MS, our proposed method helps with management of the temporal changes in MS risk. For example, let us assume that a young-male subject regularly examines the values of MS risk factors. At some time, if the ASD value of the subject exceeds the threshold for young males, the statuses of each risk factor will be investigated and risk factors approaching each threshold could be managed by a physician. Also, during the following regular examinations, not only calculation of ASD, but also the generation of a weighted radar chart could be used to analyze the temporal changes of the subject. Once the ASD value of the subject is reduced to below the threshold, only the ASD value would be used to regularly manage the subject's health.

Furthermore, since patients with chronic diseases including MS typically stay outside of hospitals for the majority of chronic disease care cycles except routine hospital visits, providing application for personal devices can help patients with self-management. Fig. 13 shows the prototype implementation of MS risk quantification application. Our prototype system is implemented on the Android 4.2 smartphone platform for easy use. By regularly analyzing the ASD value and the weighted radar chart of MS risk factors, it is possible to manage the temporal progress of MS.

IV. Conclusion

To resolve the weaknesses of current MS diagnosis methods, this paper proposed a risk quantification model for MS, which is based on ASD analysis between weighted radar charts consisting of MS diagnostic criteria and examination results of MS risk factors of a subject. The clinical effectiveness of the proposed model was evaluated using data of a large number of subjects obtained from the KNHANES III. The evaluation results showed that the proposed model can quantify the risk of MS and effectively identify a group of subjects who can be classified into a potential risk group for having MS in the future. Using the proposed model, we can identify potential MS patients early and monitor the temporal change of the patients' statuses.

This paper contributed to identifying potential MS subjects with high risk by using the novel ASD analysis, where the definitions and diagnostic criteria for MS are ambiguous. Further, it presented the risk quantification model that can be used to prevent the incidence of MS, CVD, and T2DM through managing the status of risk factors of the identified potential MS subjects. The limitations and recommendations for further study can be summarized as follows:

1) The proposed method quantifies the risk of MS based on ASD values and determines ASD thresholds for identifying individuals with MS risk. However, to further test the validity of the ASD method, a longitudinal study should be performed to determine ASD values in a cohort of subjects at one time point, and investigate whether the ASD values are predictive of the subsequent development of MS.
2) To apply the proposed method to other populations, examination results of sample subjects that statistically represent the populations are required. Without the collected examination data, it is difficult to use this method.
3) The relative weights of MS risk factors have been determined by counting the frequency of each risk factor. However, to accurately determine the relative weights, further study should be performed. Several previous studies investigating the relative importance among MS risk factors can be found in [6], [12], [45], and [46].

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