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AXIOMATIC DEVELOPMENT OF HUMAN PSYCHOPHYSIOLOGICAL STRESS INDICES USING THERMODYNAMICS

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ABSTRACT

The present study involves development of an original quantitative methodology based on the principles of thermodynamics to define and measure human stress responses. The methodology combines five physiological measures (blood pressure, heart rate, finger skin temperature, facial electromyogram, and skin conductance level) to develop an *Objective Stress Index (OSI)*. The study included forty-nine medical residents (28 males and 21 females). The physiological measures were taken under three conditions during the psycho physiological test profile. The Stress-Related Physical Symptoms Inventory (SPSI) questionnaire was administered during the course of the psycho physiological procedure. The *Subjective Stress Index (SSI)*, a ratio of the severity of stress symptoms to the number of stress symptoms, was derived from the SPSI questionnaire. Without making any assumption about the distribution of the data, a nonparametric Mann-Whitney test was performed on the OSI and SSI data. The OSI results indicate that there was a significant difference in male and female stress responses. It is concluded that OSI in combination with the SSI will provide a quantitative framework for biomedical engineering researchers and practitioners to develop standards for measurement and evaluation of human stress responses.

Keywords: thermodynamics, objective stress index, stress-related physical symptoms inventory, Maxwell relations, autonomic measures.

1. INTRODUCTION

There have been numerous studies conducted during the past several decades to define and quantify stress in work and living environments. The present study is a sequel to the earlier study conducted by Boregowda and Karwowski [1] that primarily focused on modeling of human physiological stress responses. Earlier studies by Boregowda *et al*., [2, 3] and Palsson *et al*., [4] have hypothesized that the increased disorder in the human physiological system in response to stressors can be measured using entropy change. The next question is: Can this entropy change in the physiological system be equivalent to an overall stress response? The answer is yes. The increased physiological disorder due to psychological distress is equivalent to entropy change. Further, the entropy change could be interpreted to provide a quantitative measure of psycho physiological stress as shown in the next section. The Objective Stress Index (OSI) is nothing but a normalized entropy change that is derived from the thermodynamic Maxwell relations [5]. In this study the OSI includes blood pressure, heart rate, finger skin temperature, electromyogram, and skin conductance level. The Subjective Stress Index (SSI) is a ratio of the severity of subjective self-reported physical stress symptoms (SPSI_B) to the number of physical stress symptoms (SPSI_A). The nonparametric statistical analysis reveals that there is significant difference between male and female stress responses in terms of OSI while this is not true with SSI. In conclusion, the objective measures of stress in combination with the subjective stress assessment methodology could become a valuable stress measurement tool for clinical and biomedical engineering applications.

2. THEORY AND BACKGROUND

Stress has long been the subject of psychological and physiological interpretations. It was first introduced to the scientific community by Hans Selye [6, 7], the father of stress research. Since Hans Selye’s discovery of stress as a medical concept, a great deal of confusion has arisen in lay and even in scientific literature. The term stress means different things to different people. Stress is part of our daily human experience and is associated with a great variety of essentially dissimilar problems. Such problems might include medical trauma, emotional disorders, physical effort, fatigue, pain, fear, or major lifestyle changes. Stress is present in a businessman under constant pressure; a soldier in combat; in the athlete straining to win a race; and in the air-traffic controller who bears continuous responsibility for hundreds of lives. While all these subjects face quite different problems, they respond with a varying pattern of physiological, biochemical, and structural changes. All are essentially involved in coping with any type of increased demand upon vital activity, particularly adaptation to new situations. All endogenous and exogenous agents that make such demands are called stressors. Distinguishing between their widely differing specific effects and the common biologic response that they elicit is the key to proper understanding of biologic stress.

According to Hans Selye [6, 7], stress is considered as a multiple or single physiological non-specific response of the body to any demand. It could be either acute (short-term) as in running from a mad dog or chronic (long-term) as in difficult family or work situation. Through various biochemical or neural pathways, the body responds to stressful situations resulting in altered physiological functioning leading to diseases of adaptation [6]. However, there are two types of stress responses - eustress (good stress) and distress (bad stress), which are difficult to distinguish solely from a quantitative approach. Life situations such as getting married, arrival of a child, new job, etc. creates a feeling of positive expectancy leading to eustress normally associated with some physiological changes.

In the literature one can find several studies that have been conducted to develop methods to quantify stress. The efforts to quantify stress range from measuring the cause of stress to measuring the individual's reaction to stress [8]. Physiological methods of measuring stress include measurement of heart rate [9], blood pressure [10], and skin temperature [11]. As discussed by Hancock *et al*., [12], mental stress is reflected in terms of physiological responses. Some of the studies conducted by Wilson [13, 14] emphasize the use of physiological measures to evaluate mental workload in ergonomics and human factors. In general, most of these studies have examined the impact of mental stress on either one or two physiological responses. It is important to realize that looking at just one or two physiological indicators independently will not serve the purpose of our investigation of human stress physiology. Since the human system is comprised of many interconnected physiological processes controlled by a complex nervous system, the single physiological indicators of stress provide a very narrow representation of the human stress response.

3. THERMODYNAMIC STRESS RESPONSE THEORY

Thermodynamics is the study of energy interactions in systems and surroundings in the universe. A system could be any system in the universe, including the human psychophysiological system. In the scope of the present study, multiple physiological responses are combined to form stress indices to quantify the human stress responses. In the earlier studies by Boregowda *et al*., [2, 3] and Palsson *et al*., [4], only three physiological responses (blood pressure, heart rate, and skin temperature) were taken into consideration. However, the present study takes into consideration the whole human psychophysiology by including electromyogram (EMG) and skin conductance level (SCL) along with the BP, HR, and ST. In order to provide a theoretical framework for investigating the complexity of human stress responses, the existing field of Engineering Psychophysiology is re-defined under Axiom-I as:

Axiom-I. Engineering Psychophysiology is a field of study that involves the development and formulation of functionally dependent relationships between the psychological (mental stress) and physiological (BP, HR, ST, EMG, and SCL) variables of the human psycho physiological system.

When a human being is exposed to any kind of stressor, a number of physiological changes are observed. Usually there is little or no correlation between these various physiological measures. The physiological response to a stressor cannot be considered as a simple response of a single system. Rather, the response to a stressor comprises a number of different variables and appears as a complex pattern of responses in different systems. The general human stress response combines different human subsystems and their corresponding physiological responses and is defined under Axiom-II as follows:

Axiom-II. Human stress response, in general, is a thermodynamic function of both physiological strain and stressor. The stress is defined by its terminology depending on the nature of stressor, although similar physiological reactions may be caused by different stressors or stimuli.

For example, an individual may sweat due to either ambient conditions or emotional stress. The distinction is made with the help of subjective assessments or psychological methods. The Thermodynamic theory of stress response is defined according to the following logic:

Axiom-III. Thermodynamic Stress Response Theory:

Human Stress = f {Physiological strain, Stressor}

If Stressor = Psychological factor (social or emotional or life events)
Then Human Stress = Psychological Stress

If Stressor = Physical environment
Then Human Stress = Physical Stress

In summary, the stress response is defined as a non-specific response of the body to any demand. In physical scientific terms, stress is regarded as a function of strain. The relationship between stress and strain for the whole mind-body system is highly non-linear and non-homogeneous. The primary objective of the study is to develop functional relationships between psychological stressors and physiological strain using the second law of thermodynamics, which is defined under Axiom-IV as follows:

Axiom-IV. The Second Law of Thermodynamics:
L. S. Carnot (1824): In any system, some loss of energy is inevitable. Complete conversion of input energy to output work is impossible (A forecast for the existence of entropy).
R. Clausius (1887): The amount of energy in the universe is fixed; its distribution is uneven. Conversion of energy to work in a system produces an inevitable loss of energy to a lower energy area of the universe (entropy). Entropy increases as the energy of the universe seeks uniform distribution. The drive to attain this uniformity is the fundamental force of the universe.

All systems in the universe obey the second law of thermodynamics, including the human mind-body system. Several human subsystems are being analyzed to develop indices for quantifying human stress. In this

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regard, the entropy is a measure of disorder or chaos in any system in the universe. The entire human body is considered as a system of interest and its overall entropy level is defined from a thermodynamic standpoint as follows:

Axiom-V. The entropy change or entropy generation is equivalent to human stress and is a measure of disorder or chaos or activeness in the human psychophysiological (mind-body) system in response to stressors from thermodynamic or holistic (whole body) viewpoints.

The field of thermodynamics has an important role in the study of human life sciences. A famous quote by Harvard Physicist P.W. Bridgman [15] is paraphrased as follows: "It must be admitted. I think that laws of thermodynamics have a different feel from most other laws of physics. There is something more palpably verbal about them - they smell more of their human origin. The guiding motif is quite strange to the most of physics; because they are based on the universal failure of human beings to construct perpetual motion machines of either the first or second kind. Why should we expect the nature to be interested either positively or negatively in the affairs of human beings? To follow-up on this quote, Nobel Laureate Erwin Schroedinger [16] has established the fact that the human life processes are indeed thermodynamic in nature and the thermodynamic laws can be applied to examine human behavior.

4. MODELING AND FORMULATION

If psychological stress causes changes in physiological responses that can be measured, then using thermodynamic Maxwell relations, the entropy change (ΔS) can be measured in terms of measurable physiological variables. The entropy change is a measure of disorder in both psychological and physiological domains. In other words, when we look at the human psychophysiological (mind-body) system from a thermodynamic perspective, the dichotomy between mind and body states cease and they become one energy system governed by the law of entropy. It has been demonstrated that increased physiological disorder (or normalized change in entropy) in response to stressors is mathematically equivalent to objective stress index (OSI) and is re-stated as under Axiom-VI as follows:

Axiom-VI. The normalized entropy represents the ratio of the observed physiological stress response during a task to the mean relaxation response of the sample and is mathematically equivalent to an Objective Stress Index (OSI).

The above-mentioned Axiom-VI is used to develop objective stress indices for human subsystems responsible for various physiological stress responses. If physiological responses include blood pressure (BP), heart rate (HR), and skin temperature (ST), as shown in Figure-1, to be equivalent to Pressure (P), Volume (V), and Temperature (T) in a physical system, then the Objective Stress Index (OSI) I is written as follows:

$$(OSI)_I = f\ \{Blood\ Pressure,\ Heart\ Rate,\ and\ Skin\ Temperature\} \quad (1)$$

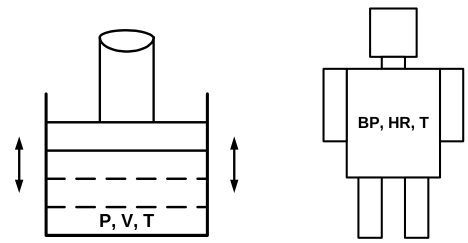

Figure-1. Similarity between mechanical and physiological systems.

By applying the Maxwell relations of thermodynamics to model the human physiological subsystem responsible for blood pressure, heart rate, and finger skin temperature, the normalized measure of entropy change in the form of $(OSI)_I$ is obtained as follows:

$$(\Delta S)_{I,Stress} = [(BP-BP_O)x(HR-HR_O)]/[ST-ST_O] \quad (2)$$

$$(\Delta S)_{I,Rel} = [(BP_{Avg.Rel}-BP_O)x(HR_{Avg\ Rel}-HR_O)] / [ST_{Avg.\ Rel}-ST_O] \quad (3)$$

$$(OSI)_I = (\Delta S)_{I,\ Stress} / (\Delta S)_{I,\ Rel} \quad (4)$$

Where,

$(OSI)_I$ = First Objective Stress Index, dimensionless.
$(\Delta S)_{I,Stress}$ = Physiological entropy change during the stressor (task).
$(\Delta S)_{I,Rel}$ = Physiological entropy change during relaxation.
BP = Average blood pressure (during relaxation, stressor, and recovery), mm Hg
HR = Average heart rate (during relaxation, stressor, and recovery), beats per minute
ST = Average finger skin temperature (relaxation, stressor, and recovery), ^{0}F
$BP_O = HR_O = ST_O = 0$ (reference states)
$BP_{Avg.Rel}$ = Average BP response of males (n=28) or females (n=21) during relaxation.
$HR_{Avg.Rel}$ = Average HR response of males (n=28) or females (n=21) during relaxation.
$ST_{Avg.Rel}$ = Average ST response of males (n=28) and females (n=21) during relaxation.

It was established that the Maxwell relations of thermodynamics can also be applied to electro-magnetic systems [5]. In this regard, the human physiological system involves electro-magnetic signatures that can be included in the Maxwell relations in a manner similar to blood pressure, heart rate, and skin temperature as in functional expression (1). If physiological responses include electromyogram (EMG), skin conductance level (SCL), and skin temperature (ST), then the (OSI) II is determined from Maxwell relations as follows:

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$(OSI)_{II}$ = *f {Electromyogram, Skin Conductance Level, and Skin Temperature}* (5)

The OSI based on electromyogram (EMG), skin conductance level, and skin temperature (ST) is defined as follows:

$$(\Delta S)_{II,Stress}=[(EMG-EMG_O)x(SCL-SCL_O)]/[ST-ST_O] \quad (6)$$

$$(\Delta S)_{II,Rel}=[(EMG_{Avg.Rel}-EMG_O)x(SCL_{Avg.Rel}-SCL_O)]/[ST_{Avg.Rel}-ST_O] \quad (7)$$

$$(OSI)_{II} = (\Delta S)_{II,\ Stress} / (\Delta S)_{II,\ Rel} \quad (8)$$

Where,

$(OSI)_{II}$ = First Objective Stress Index, dimensionless.
$(\Delta S)_{II,Stress}$ = Physiological entropy change during the stressor (task).
$(\Delta S)_{II,Rel}$ = Physiological entropy change during relaxation.
EMG = Average facial electromyogram (relaxation, stressor, and recovery), µV
SCL = Average skin conductance level (relaxation, stressor, and recovery), µmho.
ST = Average finger skin temperature (relaxation, stressor, and recovery), 0F.
$EMG_O = SCL_O = ST_O = 0$ (reference states)
$EMG_{Avg.Rel}$ = Average EMG response of Males (n=28) or Females (n=21) during relaxation.
$SCL_{Avg.Rel}$ = Average SCL response of Males (n=28) or Females (n=21) during relaxation.
$ST_{Avg.Rel}$ = Average ST response of Males (n=28) and Females (n=21) during relaxation.

The total stress level is indicated by the Objective Stress Index $(OSI)_T$ and is now developed to provide a quantitative measure of psychophysiological stress in terms of five physiological responses (blood pressure, heart rate, skin temperature, electromyogram, and skin conductance level) in the form of a single number. The $(OSI)_T$ is an additive combination of two stress indices, $(OSI)_I$ and $(OSI)_{II}$, which represent two different human psychophysiological systems, respectively. It is based on the additive property of entropies of subsystems from thermodynamics [5], which is stated as Axiom-VII as follows:

Axiom-VII. The total entropy of a system is the sum of entropies of subsystems.

The two stress indices, $(OSI)_I$ and $(OSI)_{II}$, provide a quantitative measure of physiological disorder or stress in the respective human subsystems. The next step is to combine the Equations (4) and (8) to obtain total stress response as shown:

$$(OSI)_T= (OSI)_I + (OSI)_{II} \quad (9)$$

Equation (9) is the basis for mind-body interaction model and it would add significant value to the existing body of knowledge. In final analyses, the overall Objective Stress Index (OSI) can be defined in the functional form as follows:

$$(OSI)_T = f\ \{BP, HR, ST, EMG, SCL\} \quad (10)$$

At a macroscopic level, the human physiological system behaves like a magneto-electro-mechanical system, producing physiological signatures - BP, HR, ST, EMG, and SCL. The normalized entropy change, which is used to combine these signatures, quantitatively represents stress occurring in the mind-body energy domain. This logic is quite similar to the one developed by Fechner [17] that "Physical Measurement yields a Psychic Measurement, on which we can base our arguments that in their turn are of importance and interest." It is expressed in the functional form as:

$$PSYCH = f\ (PHYSICAL) \quad (11)$$

To support the above statement by Fechner, according to Morowitz [18]…"Cartesian mind-body dualism and modern versions of this viewpoint posit a mind thermodynamically unrelated to the body but informationally interactive. The relation between information and entropy developed by Leon Brillouin [19] demonstrates that any information about the state of a system has entropic consequences. It is therefore impossible to dissociate the mind's information from the body's entropy. Knowledge of that state of the system without an energetically significant measurement would lead to a violation of the second law of thermodynamics"

By following the above argument, the Total Objective Stress Index $(OSI)_T$ is a measure of the physiological reflection of any psychological process and thus characterizes the mind-body interaction as indicated in final Axiom-VIII:

Axiom-VIII. The non-dimensional total entropy change is a measure of disorder in a human psychophysiological system. It could be regarded as equivalent to the human stress response and is mathematically represented by the total Objective Stress Index $(OSI)_T$ as shown in the following expression:

$$Human\ Stress\ Response = (OSI_T) = f\ \{BP, HR, ST, EMG, and\ SCL\} \quad (12)$$

Expression (12) states that the objective measure of stress is dependent on multiple physiological responses. If single physiological indicators such as blood pressure can give a measure of stress, why do we need a composite measure of stress? The answer is: The psychophysiological concepts such as stimulus response (SR) specificity, organ response (OR) specificity, individual response (IR) specificity, and autonomic balance (AB) make the human stress response a complex phenomena [20]. In order to overcome this complexity, this present study was undertaken to combine different physiological measures in a meaningful manner using Maxwell relations of thermodynamics. In other words, an effort has been made to reduce the complexity of human stress response into a single index that could be used as a parameter to quantify the mind-body interaction. Further, this model will provide an excellent basis for generating substantial clinical data for evaluating the effectiveness of occupational health interventions and stress management programs.

The derivation of Subjective Stress Index (SSI) is quite straightforward and is defined by Postulate IX as follows:

Axiom-IX. The Subjective Stress Index (SSI) is a measure of self-reported physiological disorder and is a ratio of the severity of physical stress symptoms to the actual number of symptoms.

The Subjective Stress Index (SSI) is derived as follows:

$$SSI = SPSI\_B/SPSI\_A \tag{13}$$

Where, SPSI_B = Severity of physical stress symptoms (refer to Appendix)
SPSI_A = Number of physical stress symptoms (refer to Appendix-C)

5. METHODS

5.1 Subjects

The data in the study was collected on forty-nine senior medical students and family medicine resident physicians, 21 females and 28 males with a mean age of 28.8 years. These subjects completed a standard psychophysiological stress profile procedure routinely used for clinical assessment in the Behavioral Medicine Clinic at Eastern Virginia Medical School. The participants were all healthy (without any major health problems).

5.2 Data collection

The physiological data was collected by a ProComp + biofeedback system connected to a Dell 166 MHz PC computer running a MultiTrace biofeedback software for data processing and analysis, as well as a stand-alone Dinamap 1846 Vital Signs Monitor (Critikon Inc., Tampa, FL). The subjects completed the Stress-Related Physical Symptoms Inventory (SPSI) before the stroops test was administered. The Psychological Stress Profile is a 20-minute standard testing sequence consisting of three following conditions:

Condition-1 (Relaxation Period)

Relaxing in semi-reclining position with eyes open for three minutes followed by relaxing with eyes closed for three minutes (Total time = 6 minutes).

Condition-2 (Stressor Period)

Solving a series of forty, six-second long cognitive tasks presented on a computer screen. The tasks, Stroops type color-naming and arithmetic problems, are alternated. The sequence of problems is the same for all subjects (Total time = 8 minutes).

Condition-3 (Recovery Period)

Relaxing again with eyes open for three minutes followed by relaxing with the eyes closed for three minutes (Total time = 6 minutes).

With the Dinamap Vital Signs Monitor and a mechanically inflated pressure cuff around the subject's right arm, the blood pressure and heart rate recordings are made three times along with finger skin temperature, facial electromyogram, and skin conductance level. The physiological recordings are made after Conditions-1 (relaxation period), 2 (stressor period), and 3 (recovery period), respectively. These values are averaged for calculating the objective stress indices as illustrated in the next section.

The Stress-Related Physical Symptoms Inventory (SPSI) developed by Palsson *et al.*, [4] is a paper-and-pencil self-report inventory where subjects are asked to indicate whether they have experienced each of thirty-two symptoms during the past month. The symptoms listed are all bodily symptoms which are considered by many health professionals to be common physical manifestations of stress. The symptoms listed include stiff muscles, excessive sweating, dry mouth, chest pain, shortness of breath, and cold hands or feet. The instructions ask the subjects not to indicate any of the listed symptoms which are known to be related to a diagnosed physical illness or due to medications the subject might be taking. The instructions on the SPSI also ask the subjects to indicate how frequently they have experienced the indicated symptoms. The SPSI presented in the Appendix includes two measures, with SPSI_A denoting the number of physical stress symptoms and SPSI_B the severity of physical stress symptoms.

5.3 Illustrative example

It should be noted that the diastolic blood pressure (DBP) is used in the computation of objective stress index. Each one of the physiological measures - DBP, HR, ST, EMG, and SCL used in the calculation of objective stress indices are average values of the three conditions. For example, let us consider the diastolic blood pressure of one of the male subjects under three conditions as follows:

Condition-1 (Relaxation): $(DBP)_1 = 69.00$ mm Hg
Condition-2 (Stressor): $(DBP)_2 = 75.00$ mm Hg
Condition-3 (Recovery): $(DBP)_3 = 61.00$ mm Hg

The average value of diastolic pressure is given by:

$$DBP = (DBP_1 + DBP_2 + DBP_3)/3.0 = 68.33 \text{ mm Hg}$$

In a similar manner the remaining average values of heart rate, skin temperature, electromyogram, and skin conductance level are calculated as follows:

DBP = 68.33 mm Hg
HR = 61.00 bpm
ST = 89.06 0F
EMG = 2.95 μV
SCL = 7.10 μmho

The normative or baseline values of physiological measures represent dead states and are stated as follows with $DBP_O = HR_O = ST_O = 0$. The average values of physiological measures are obtained during the relaxation phase of the experiment and they are given as follows for the male subjects (N=28):

$DBP_{Avg.\ Rel}$ = 67.89 mm Hg
$HR_{Avg.\ Rel}$ = 56.71 bpm
$ST_{Avg.\ Rel}$ = 84.61 0F
$EMG_{Avg.\ Rel}$ = 2.03 µV
$SCL_{Avg.\ Rel}$ = 3.85 µmho

The Objective Stress Index, $(OSI)_I$, based on diastolic blood pressure, heart rate, and skin temperature is calculated as follows:

$(\Delta S)_{I,Stress}$ = [(68.33-0.0) x (61.00-0.0)] / [89.06-0.0] = 46.80 mm Hg.bpm/0F
$(\Delta S)_{I,Rel.}$ = [(67.89-0.0) x (56.71-0.0)] / [84.61-0.0] = 45.50 mm Hg.bpm/0F
$(OSI)_I = (\Delta S)_{I,\ Stress} / (\Delta S)_{I,Rel}$=46.80/45.50 = 1.03 stress units

The Objective Stress Index, $(OSI)_{II}$, based on electromyogram, skin conductance level, and skin temperature is calculated as follows:

$(\Delta S)_{II,Stress}$ = [(2.95.33-0.0) x (7.10-0.0)] / [89.06-0.0] = 0.235 µV. µmho/0F
$(\Delta S)_{II,Rel}$. = [(2.03-0.0) x (3.85-0.0)] / [84.61-0.0] = 0.09 µV. µmho/0F
$(OSI)_{II} = (\Delta S)_{II,\ Stress} / (\Delta S)_{II,Rel}$=0.235/0.09= 2.61 stress units

The total value of the Objective Stress Index $(OSI)_T$ that includes diastolic blood pressure, heart rate, skin temperature, electromyogram, and skin conductance level is defined by Equation (9) and calculated as follows:

$(OSI)_T = (OSI)_I + (OSI)_{II}$=1.03 + 2.61=3.64 stress units

The $(OSI)_T$ value of 3.64 stress units represents the quantitative measure of disorder in the human psychophysiological system of one of the selected male subjects.

Consider the same male used previously to compute SSI. Now, let us compute the Subjective Stress Index (SSI) units for this subject. The SPSI_A and SPSI_B scores and the subsequent calculation of SSI are given below:

SPSI_A = 7.0
SPSI_B = 12.0
SSI = SPSI_A / SPSI_B = 7.0 / 12.0 = 1.71 stress units

By following this illustrative example, the reader can understand the mathematical details behind this concept of stress measurement.

6. RESULTS AND ANALYSIS

Readers are referred to the end of the document for Figures 2-5 and Tables 1-3 pertaining to this section. The data analysis is performed to demonstrate the utility of the total Objective Stress Index $(OSI)_T$ for use in stress evaluation and human performance analysis. Table-1 includes the anthropometric data from a healthy sample of 28 male and 21 female medical residents, who participated in the experimental study. Table-2 provides OSI and SSI statistics for both males and females. This includes average, median, standard deviation, and range with minimum and maximum. Table-2, in combination with the Figure-2 (for males) and Figure-3 (for females), will provide a quantitative view of variation of stress among the male and female subjects, respectively.

It is visually observed from Figures 2 and 3 that the stress response in male and female subjects appears to be different. However, one of the objectives of this study is to demonstrate the utility of objective stress indices to detect a significant difference in the stress response between male and female subjects. In order to make any parametric statistical inference about the data, a normality test was conducted using MINITAB software [21] on all the data streams for both male and female stress responses, respectively as shown in Figures 4 and 5. One of the statistical conditions for normality is that the p-value has to be greater than 0.05, the level of significance. It is clear from Figure-4 that most of the male stress response data streams do not follow normal distribution except for the subjective stress index, SSI (p-value, P=0.609). This is identified from the fact that p-values (P) in Figure-4 are less than the level of significance, $\alpha = 0.05$ except for SSI. However, Figure-5 reveals that only $(OSI)_{I\text{-}F}$, the diastolic blood pressure-based female stress response, follows normal distribution (p-value, P = 0.793) while others are marginally normal with p-values (P) slightly larger than 0.05, the level of significance. In order to make any further statistical inference, a nonparametric Mann-Whitney test was conducted to detect differences between male and female stress responses as shown in Table-3.

Table-3 reveals that there is a significant difference between male and female objective stress responses derived from blood pressure expressed in terms of $(OSI)_I$. This is not true with EMG-derived objective stress responses, $(OSI)_{II}$, as indicated in the row two of the Table-3. However, with regard to total objective stress response represented by $(OSI)_T$, there is a significant difference between males and females. When it comes to self-reported subjective stress scores, there was no significant difference between males and females. The paradox is that there is a significant difference between male and female stress responses when it comes to the total objective stress index $(OSI)_T$, while there is no such significant difference with regard to self-reported subjective responses expressed in terms of the subjective stress index (SSI). Suppose we had used only objective methodology using OSI, we would have concluded that there is a significant difference in male and female stress responses. On the other hand, if we had conducted only subjective assessment of stress, we would have concluded that there was no such difference. In conclusion, the proposed thermodynamic-based OSI methodology in combination with an appropriate subjective stress assessment questionnaire using SSI would be valuable to researchers to make effective clinical decisions in medical research.

CONCLUSIONS

The results from this study offer some preliminary indications suggesting that the OSI may be a valuable index to detect vulnerability of the human body to various levels of stress. The finding of a statistically significant difference in the population mean OSI values between males and females indicates that there is a great potential for use of OSI. It could be a much better measure of stress than single physiological indicators. The Mann-Whitney test results show there is a statistically significant difference between male and female OSI stress responses. The same nonparametric statistical analysis indicates that there is no statistically significant difference between male and female SSI stress responses. As a result of this paradox, it is suggested that the OSI, along with the SSI, could become a robust methodology for measurement and evaluation of stress in work and living environments. The Objective Stress Index (OSI) in combination with Subjective Stress Index (SSI) could be used to provide a measure of stress and predict health risk due to stressful life conditions. This unified stress measure could provide the fields of behavioral medicine, psychology, and public health sciences in general with something which has long been sorely missing - a scientifically sound and clinically useful way of quantifying human stress as a single number.

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Appendix-A: Tables

Table-1. Anthropometric data (Male and female subjects).

	Age (Years)		**Height** (Inches)		**Weight** (lbs)	
	Male (n=28)	**Female** (n=21)	**Male**	**Female**	**Male**	**Female**
Mean	28.43	29.20	68.46	65.07	168.43	140.14
Median	26.00	26.00	68.50	65.00	165.00	130.00
SD	5.00	9.12	4.34	2.06	30.62	34.70

Table-2. Comparing male and female stress responses.

	OSI (Objective Stress Units)		**SSI (Subjective Stress Units)**	
	Males (n_1=28)	**Females** (n_2=21)	**Males** (n_1=28)	**Females** (n_2=21)
Mean	3.61	2.66	1.94	2.07
Median	2.92	2.42	1.95	2.00
SD	2.25	1.03	0.43	0.44
Min	1.04	1.26	1.20	1.54
Max	8.99	5.13	2.67	3.10

Table-3: Difference between male and female stress responses using Mann-Whitney test.

Indices	**Median values**		**Point estimate of difference in median**	**p-value**
	Males (n=28)	**Females** (n=21)		
$(OSI)_I$	1.0145	0.9539	0.1380	0.0423
$(OSI)_{II}$	1.7700	1.3970	0.2070	0.5785
$(OSI)_T$	2.8140	2.0290	0.7430	0.0466
SSI	1.9545	2.0000	-0.1130	0.4915

Appendix-B: Figures

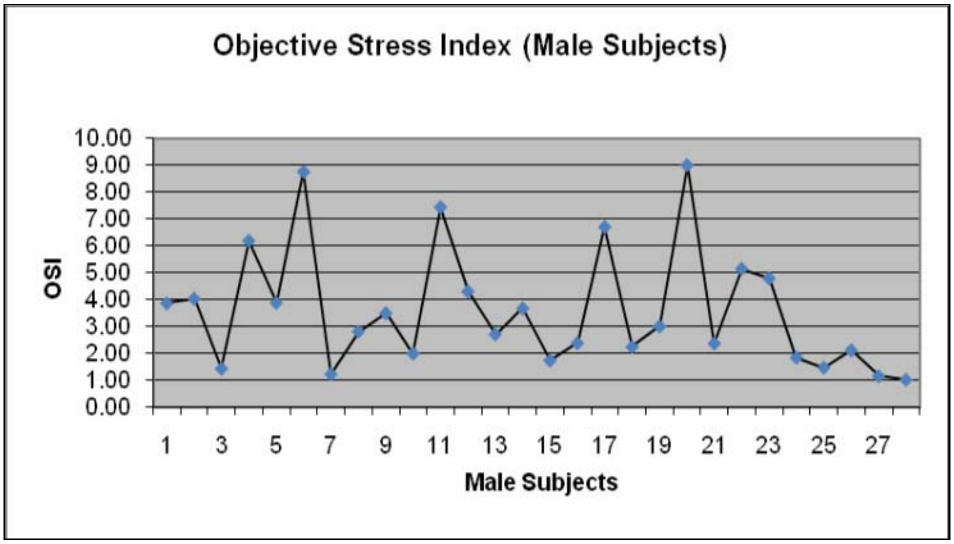

Figure-2. Variation of objective stress among male subjects.

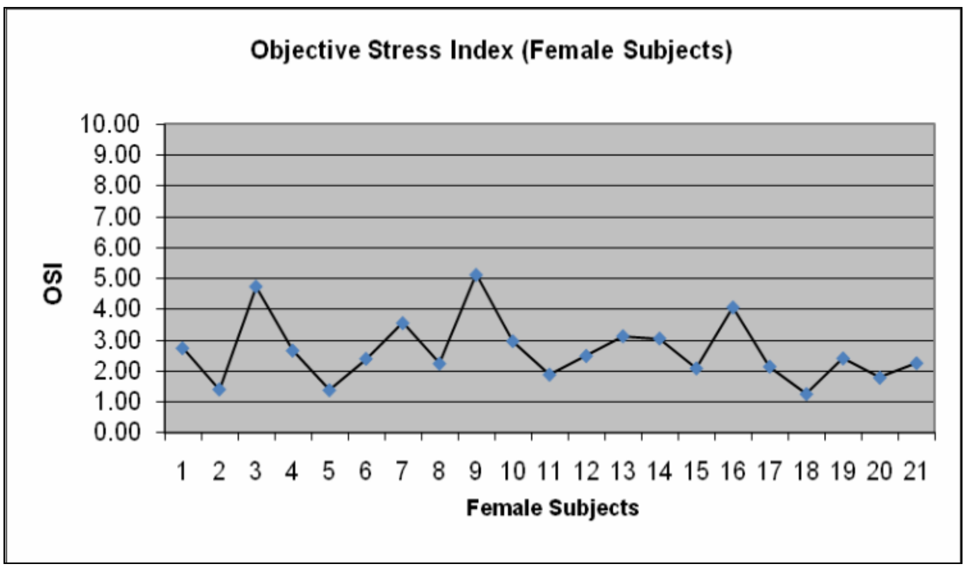

Figure-3. Variation of OSI among female subjects.

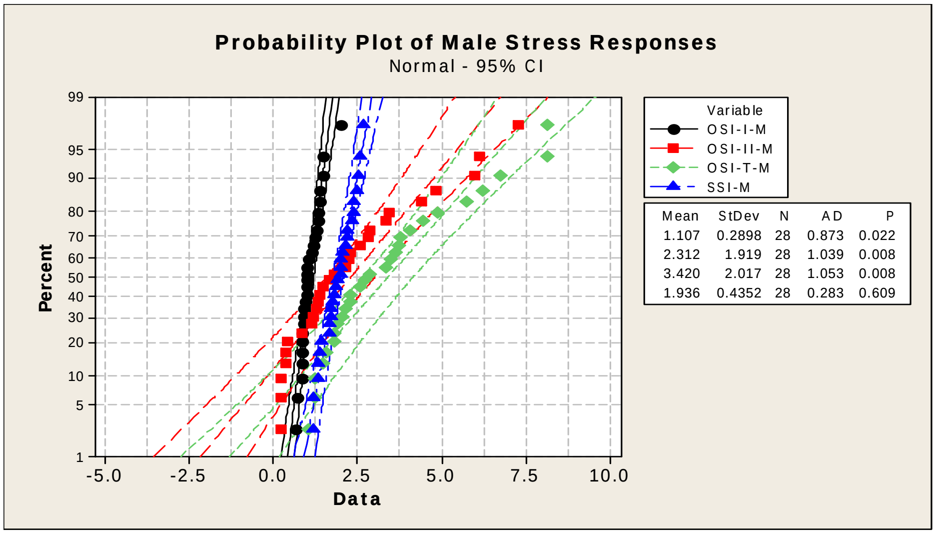

Figure-4. Normality test on $(OSI)_{I-M}$, $(OSI)_{II-M}$, $(OSI)_{T-M}$, and $(SSI)_{M}$.

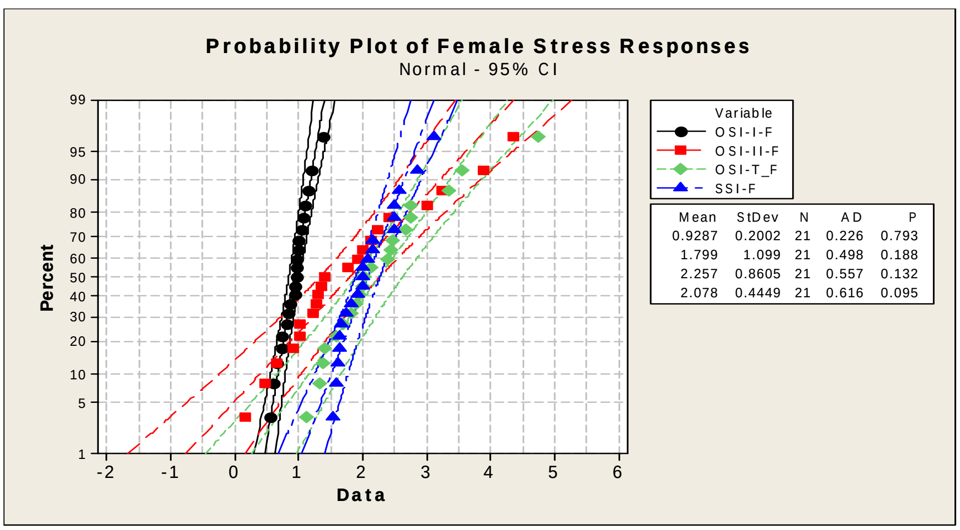

Figure-5. Normality test on $(OSI)_{I-F}$, $(OSI)_{II-F}$, $(OSI)_{T-F}$, and $(SSI)_{F}$.

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Appendix-C. Stress-related Physical Symptoms Inventory (SPSI).

Please indicate by circling one number how often you have had each symptom DURING THE LAST ONE MONTH. DO NOT include symptoms which are diagnosed organic (physical) illness or caused by medications you are taking.

	Never	Once	Occasionally	Often	Always
1. Cold hands or feet	0	1	2	3	4
2. Stiff muscles	0	1	2	3	4
3. Headache	0	1	2	3	4
4. Back pain	0	1	2	3	4
5. Chest pain	0	1	2	3	4
6. Abdominal pain	0	1	2	3	4
7. Jaw pain (or TMJ)	0	1	2	3	4
8. Pain other than 3-7 above	0	1	2	3	4
9. Sleep difficulties	0	1	2	3	4
10. Dizziness	0	1	2	3	4
11. Diarrhea	0	1	2	3	4
12. Physical fatigue	0	1	2	3	4
13. Excessive sweating	0	1	2	3	4
14. Fast (racing) heart beat	0	1	2	3	4
15. Shortness of breath	0	1	2	3	4
16. Eye twitching	0	1	2	3	4
17. Asthma attacks	0	1	2	3	4
18. Allergic reactions	0	1	2	3	4
19. Constipation	0	1	2	3	4
20. Dry mouth	0	1	2	3	4
21. Nausea or vomiting	0	1	2	3	4
22. Teeth grinding (bruxism)	0	1	2	3	4
23. Poor appetite	0	1	2	3	4
24. Sexual difficulties	0	1	2	3	4
25. Restlessness	0	1	2	3	4
26. Unexplained skin rash	0	1	2	3	4
27. Trembling hands	0	1	2	3	4
28. Blurred vision	0	1	2	3	4
29. Weak or wobbly	0	1	2	3	4
30. Easily startled (jumpy)	0	1	2	3	4
31. Flushing the face	0	1	2	3	4
32. Difficulty swallowing	0	1	2	3	4

Scoring: SPSI_A ________ = TOTAL # of NON-ZERO RESPONSES
SPSI_B ________ = TOTAL SUM OF CIRCLED NUMBERS
SSI ________ = SPSI_B / SPSI_A