CHANGES IN HEART RATE VARIABILITY DURING A SIMULATED ASSEMBLY TASK

by

Angel Marie Nardolillo

May 12, 2017

A thesis submitted to the Faculty of the Graduate School of the University at Buffalo, State University of New York in partial fulfillment of the requirements for the degree of Master of Science

Department of Industrial and Systems Engineering

TABLE OF CONTENTS

I. ABSTRACT…………………………………………………………….................iii

II. INTRODUCTION……………………………………………………………………1

III. METHODS…………………………………………………………………………..2-5

i. **PARTICIPANT**

ii. **PROCEDURES**

iii. **OBJECTIVE MEASURES**

iv. **SUBJECTIVE MEASURES**

v. **STATISTICAL ANALYSIS**

IV. RESULTS……………………………………………………………………..……..5-8

i. **DESCRIPTIVE RESULTS**

ii. **STATISTICAL COMPARISON**

V. DISCUSSION………………………………………………………………........8-10

VI. LIMITATIONS AND STRENGTHS…………………………………………...10-11

VII. CONCLUSIONS…………………………………………………………………..11

VIII. REFERENCES………………………………………………………...………12-13

ABSTRACT

Attention has been concentrated on productivity in manufacturing settings with assembly line tasks being a common area of focus. Prolonged fatigue can occur during various assembly tasks both cognitively and physically. This can place a damper on efficiency and productivity for workers in manufacturing. There is opportunity to better understand fatiguing during a typical assembly structure task so that fatigue patterns can be identified. Intercession can subsequently take place centered around reducing excessive workload tasks to assure a worker's mental and physical thresholds are not contravened.

Fatiguing can be better understood by a person's physiologic measures specifically their heart rate. Heart rate variability (HRV) is a successful indicator for identifying heart rate variations. Calculations are performed between each beat that can objectively quantify human capacity levels and the onset of fatigue. This study considers HRV during an assembly line task and compares differences in cardiac parameters between younger and older participants. The results obtained from this study were used to better understand fatiguing during the task at each segmented time interval.

The HRV outcomes exhibited an index for each interval which gave the ability to make improved task demand decisions within the assembly line assignment. Statistical differences between age groups were also prominent which gave notion that workplace tasks should consider age classification when designing work structures for employees. This study assessed the potential function of HRV during a simulated task by examining the autonomic responses of the heart. The relationship between the autonomic nervous system and HRV were examined.

INTRODUCTION

Heart rate variability (HRV) is a commonly used physiological measure that objectively quantifies human workload giving researchers the ability to evaluate the subconscious response during a dynamic or static task. HRV can discern fluctuating task demands and historically it has revealed to attenuate during mentally straining workloads (Yijing, 2015). This physiological measure offers researchers a paradigm into the recovery process after the body has been exerted from a task. Researchers can subsequently create optimal training programs within exercise science disciplines based on these measures (Dong, 2016). Similarly, task performance structures can be designed within industry settings based on HRV results to better accommodate an employee's ideal workload.

The autonomic nervous system (ANS) is the regulating system controlling HRV and can be divided into two types of classifications that is: parasympathetic and sympathetic branches (Medeia, 2017). These branches have regulating levels that fluctuate on a continuous basis. An increase in parasympathetic activity will decrease a person's heart rate and increase the HRV. On the opposing side, the sympathetic involvement will demonstrate an increase in heart rate and decrease in HRV parameters.

HRV has been known to decrease during periods of increased cognitive strain and workload stress. The objective of this study was to utilize HRV as a fatigue indictor to better understand the physiological stresses of the task workload and associated subjective measures. It was hypothesized that over time the participants would become fatigued and the cardiac variability along with the subjective fatigue analyses would successfully indicate the changes during each time point of the task.

METHODS

PARTICIPANT

Data was collected from 20 subjects that participated in a simulated assembly line task experiment while having their heart rate recorded. There were a total of seven females and thirteen males recruited for the study. The subjects ranged in age from 19-65 years ($\bar{x}$= 36.95, σ = 16.61). Participants were recruited from the university and local community, with approximately half employed in outside jobs such as construction and manufacturing. The participants were divided into two equally sized groups based on age classification (n=10). Group one ranged from 19- 29 and the second group ranged 30-65 years of age. The experimental protocol was approved by the university's Institutional Review Board and all participants provided written informed consent.

PROCEDURES

A part assembly operation was performed using Erector Assembly Kits to build parts based on visual work instructions. Diagram 1 displays the work instructions that were used to complete the two required subassemblies for the erector car. Steps 1-4 were followed preceding steps 5-8. The sub-assembly required the participants to perform tasks that were representative of common assembly task motions. The work instructions were reviewed with the participants prior to assembly and were also available to them during the task operation.

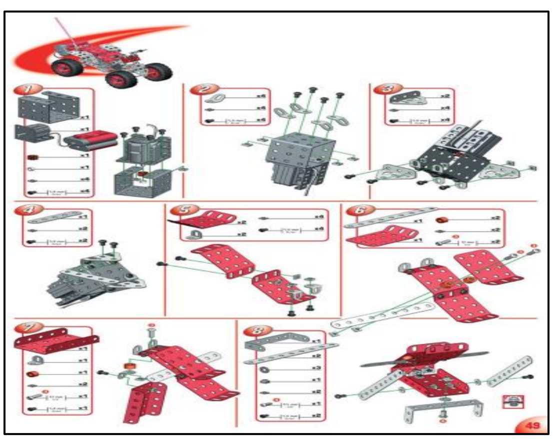

Diagram 1: Erector Assembly Kit

While the participants performed the task, they maintained a standing position over three one-hour periods. Standing posture is a widely-adopted stance throughout workplace settings it also increases the likelihood of inducing physical fatigue. This task was performed as part of a larger study and additional details can be found in (Maman, 2017). There were several reasons behind selecting the standing posture for this assignment. The main reason was because this posture can irritate physical fatigue when adopted for long hours causing the onset of lower back pain and solidness in the neck or shoulders (Maman, 2017). Secondly, this posture decreases the blood flow to the muscles, quickens the onset of physical fatigue, and causes pain in the leg, back and neck muscles (Maman, 2017). Another study concluded that the standing position is most advantageous for evaluating HRV by spectral analysis (Ravé, 2016).

Each participant wore a Polar heart rate monitor to record the inter-beat interval of the heart rate. Prior to the Polar strap application, the plastic electrode area on the reverse side was moistened. The strap was then applied to each participant and adjustments to the length were made so it fit tightly around the chest. The strap was carefully applied below the chest muscles to ensure that a clear signal was obtained. There was enough room for the middle and index finger to fit between the inside of the strap and the participant's skin.

Baseline heart rate and HRV data was collected while the participants were in a supine position to establish a starting point for each of the subject's heart rate. Following this, participants completed the standing simulated assembly line task and the heart rate was captured throughout the three hours of task until completion.

OBJECTIVE MEASURES

After the data was collected it was downloaded into the Kubios HRV Software program for data analysis. Ten minute intervals were selected for each participant which covered the start of the task, after one hour, after two hours, and after three hours. The baseline resting files were also evaluated for each of the participants for a total length of two-minutes. All of the data had a strong level of artifact correction to better filter the results and to eliminate any noise.

The time domain measures used were Mean R-R interval (i.e. heart rate), standard deviation of the normal to normal R-R intervals (SDNN) and the root mean square of successive R-R interval differences (RMSSD); followed by the geometric derivatives normal RR, and triangular interpolation of normal to normal (TINN). Lastly, the frequency domain indices making up this study were low frequency content (LF), high frequency content (HF), and LF/HF ratio.

SUBJECTIVE MEASURES

Two approaches were used to track the mental state of the participants' perceived workload: the NASA TLX and subjective fatigue score. The purpose behind using different subjective measures in the same experiment was to build an overall foundation of the participant's level of fatigue. These two approaches are strategic methods since they are timely to use and easy to administer. This approach also minimally disrupts the overall framework of the task.

The NASA TLX measured the participants' cognitive load throughout the assembly process on a multidimensional level. This questionnaire was given to all of the participants at the end of each hour. The expectation was that NASA TLX scores would increase from the first hour mark to the end of the task since the participants were performing the assembly task across the three-hour duration.

STATISTICAL ANALYSIS

Minitab 17 Software was used to perform data analysis and results were considered statistically significant with a $p\text{-value} < 0.05$ for the classifications of this study. Differences in task time intervals were assessed using a general linear model (i.e. ANOVA). Multiple residual plots were created for each HRV parameter prior to ANOVA interpretation, allowing for validation of the four key assumptions. All of the eight parameters met the key assumptions without having to make transformations to the data sets. A Pearson product-moment correlation was used to compare between physiologic responses and subjective fatigue ratings making it possible to measure the linear dependence between each variable.

RESULTS

DESCRIPTIVE RESULTS

HRV Outputs Young vs. Old					
Identification Key: O=Older, Y=Younger					
Working Position	**Task Time**	**HRV Parameter**	**Age**	$\bar{x}$	σ
Supine	Resting	SDNN	O	59.2	15.8
			Y	62.7	13.5
		RMSSD	O	34.4	17.7
			Y	48.3	17.1
		Norm. RR	O	10.6	3.1
			Y	12.1	3.0
		TINN	O	223.5	63.5
			Y	259.5	45.5
Standing	Start	SDNN	O	41.3	15.7
	Start		Y	49.1	11.4
	1 Hour	SDNN	O	51.3	18.3
	1 Hour		Y	55.0	14.0
	2 Hour	SDNN	O	91.1	69.6
	2 Hour		Y	49.4	11.7
	3 Hour	SDNN	O	52.4	20.1
	3 Hour		Y	60.7	19.7
Standing	Start	RMSSD	O	20.9	16.7
	Start		Y	22.1	6.2
	1 Hour	RMSSD	O	24.9	17.1
	1 Hour		Y	25.8	11.2
	2 Hour	RMSSD	O	51.7	88.6
	2 Hour		Y	23.8	10.0
	3 Hour	RMSSD	O	27.0	18.2
	3 Hour		Y	34.2	24.0
Standing	Start	Norm. RR	O	10.7	3.8
	Start		Y	12.3	3.4
	1 Hour	Norm. RR	O	12.5	3.6
	1 Hour		Y	13.3	3.4
	2 Hour	Norm. RR	O	16.1	5.0
	2 Hour		Y	11.8	2.5
	3 Hour	Norm. RR	O	13.9	5.5
	3 Hour		Y	15.7	5.3
Standing	Start	TINN	O	207.5	77.3
	Start		Y	243.0	57.7
	1 Hour	TINN	O	249.5	70.5
	1 Hour		Y	270.0	71.9
	2 Hour	TINN	O	327.5	126.1
	2 Hour		Y	240.0	51.9
	3 Hour	TINN	O	248.5	74.2
	3 Hour		Y	285.5	73.8

Table 1: Age Classified Descriptive Stats.

Table 1 displays the time domain parameters for the participants broken down by age group. The table provides representation of the changes in the average HRV while the participants were between the supine and standing positions. The younger group (19-29 years of age) displayed a higher trending mean for each of the parameters in the supine, task start, one-hour, and three-hour period. There was a shift at the two-hour mark with a lower mean in the time domain parameters for the younger population compared to the older population. Two boxplots were created to compare the one-hour mark of the task to the end of the task (Figures 1 and 2). This allowed for increased understanding of the perceived cognitive workload. Overall, both the NASA TLX and subjective fatigue scales displayed an increased shift in with higher workload at the three hour point compared to the one hour point (Figure 1: 1-hour Median=37.0, 1-hour IQ Range=

21.75 versus 3-hour Median= 47.5, 3 hour IQ Range= 42.25) and (Figure 2: 1-hour Median= 3.0, 1-hour IQ Range= 0.75 versus 3-hour Median= 6.0, 3 hour IQ Range= 4.0).

STATISTICAL COMPARISON

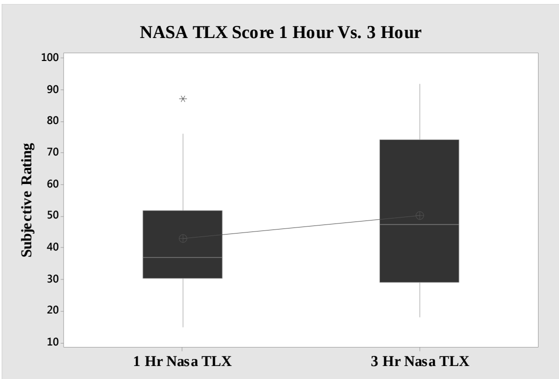

Figure 1: NASA TLX Boxplot

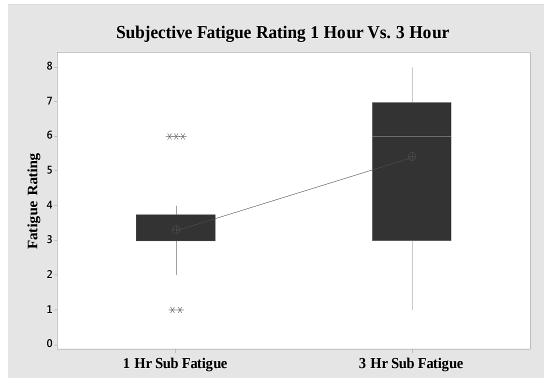

Figure 2: Subjective Fatigue Boxplot

Comparisons between participants and task time intervals were reviewed in order to properly differentiate various segments during the assembly line task and the *p* values for the comparisons displayed in Table 2 (0= Baseline supine, 1= task start, 2= 1-hour, 3= 2-hour, and 4= 3-hour). The 2-1, 4-1, 4-2, and 4-3 task types represent shared means across each parameter. Conversely, the Mean RR, LF, HF, and LF/HF shared differences when compared to the baseline starting supine position across the four durations. The time domain parameters had 76% similar means

Kubios HRV Analysis		*Task Type Comparison*									
Time Domain Analysis		1--0	2--0	3--0	4--0	2--1	3--1	3--2	4--1	4--2	4--3
	Mean RR*	0.00	0.00	0.00	0.00	0.72	0.02	0.01	0.33	0.19	1.00
	SDNN	0.28	0.89	0.62	0.99	0.82	0.01	0.53	0.14	0.99	0.34
	RMSSD	0.17	0.38	1.00	0.76	0.99	0.31	0.82	0.58	0.97	0.92
	RR Triangular Index	0.99	0.20	0.01	0.00	0.39	0.02	0.00	0.70	0.15	0.84
	TINN	0.97	0.70	0.08	0.45	0.32	0.01	0.15	0.67	0.99	0.89
Frequency Domain Analysis											
	LF	0.00	0.00	0.00	0.00	0.99	0.99	0.99	1.00	0.86	0.89
	HF	0.00	0.00	0.00	0.00	0.99	0.99	0.99	1.00	0.86	0.89
	LF/HF	0.00	0.00	0.00	0.00	0.92	0.98	1.00	1.00	0.94	0.99
P-Value of < 0.05 was considered to be statistically significant											

Table 2: Differentiating Means by Task Type

with 24% unequal for the task type comparisons. The HRV measures demonstrating differentiating means were for the Mean RR, SDNN, RR Triangular Index, and TINN.

The time domain indices were decreased in male participants when compared to females (Mean RR (male= 693 +/- 52.7 vs. females= 713.9 +/- 36.8) SDNN (male = 42.6 +/- 13.5 ms vs. females = 50 +/-14.5 ms), RMSSD (male = 21.1 +/- 14.6 ms vs. females = 22.29 +/-7.03 ms), Triangular Index (male = 10.61 +/- 3.32 ms vs. females = 13.06 +/- 3.75 ms), and TINN (male = 208.5 +/- 68.2 ms vs. females = 256.4 +/-63 ms)]. Comparison of frequency domain indices; LF/HF (male = 6.63 +/- 5.05 vs. females = 6.97 +/- 4.60), LF (male = 79.7 +/- 15.7ms^2 vs.

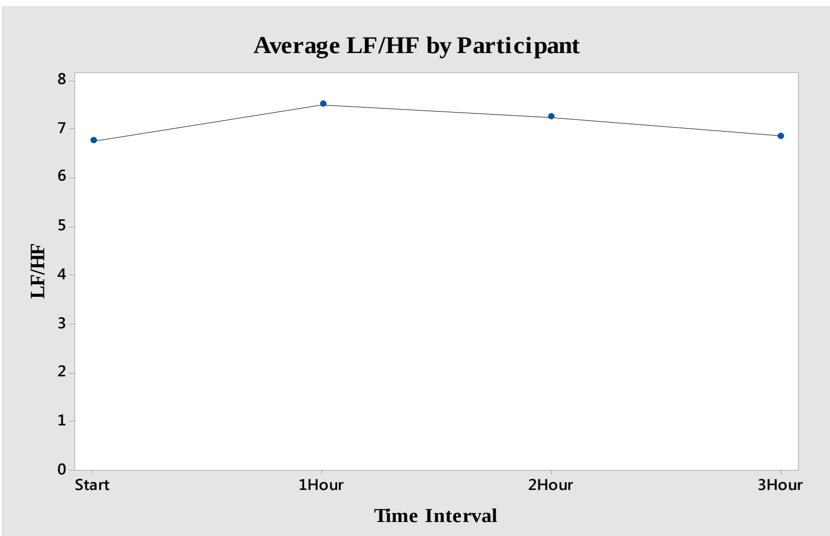

Figure 3: Frequny Domain Trend

females = 82.4 +/- 11ms^2) and HF (male = 20.2 +/- 15.6 ms^2 vs. females = 17.6 +/- 11 ms^2). From all the frequency domain parameters, HF was the only metric that displayed a higher mean for male participants. The lower HRV metrics that were demonstrated in the male participants reflect a sympathetic dominance in the participants ANS.

Figure 3 displays the average trend of all participants for the LF/HF, which displayed a steady inclined trend from the start of the task until the one-hour point followed by a decline through to the end of the task.

The relationship between SDNN and LF was examined; previous trends displayed a basis for association between these two variables. It was not until the 2-hour mark that SDNN and LF displayed significant dependence. As soon as the first hour mark was reached the R^2 values expressed a negative trend up to the 3-hour period; one-hour R^2 = -0.441, two hour R^2 = -0.648, and three hour R^2 = -0.479.

A correlation was generated to understand the relationship involving subjective and objective measures. The subjective fatigue scale was correlated to the frequency domain parameters and a significant relationship was found at the two-hour period when the participant reached the midpoint of the task (LF p-value= 0.05, R^2 = 0.443 and HF p-value= 0.05, R^2 =-0.444. Due to the limited sample size LF/HF was not found to have a significant correlation, future studies should aim to increase in sample size which may reflect on a significant LF/HF correlation (LF/HF p-value= 0.058]. The results demonstrate a significant relationship between the objective non-invasive measures and subjective measures at the midpoint of the task.

Lastly, the findings in this study demonstrated a larger mean value for the LF index ($\bar{x}$ LF = 60.02 +/- 21.33, $\bar{x}$ HF=39.75 +/- 21.25, corresponding p-value= 0.005). The t-test results displayed that these two means were significantly different.

DISCUSSION

The three-hour assembly task was designed with the intent that mental workload would increase over time and would be represented by subjective and objective measures. The assembly line intensity was kept constant from the start to the end of the task. However, due to the fatiguing effect, it was intended for the task to innately increase in difficultly for the participants.

The hypothesized concept stating that the measured HRV parameters would show statistical differences during each segment of the task yielded 67% accuracy for the time domain measures when compared to the task start versus the 2-hour interval.

The geometric measures also revealed 100% statistical differences for the task start versus 2-hour task portions. The frequency domain indices had an opposing strong trend for HRV parameters with 100% conclusiveness for failure to reject the null hypothesis assuming means were the same for the respective task type comparisons (2-1, 3-1, 4-1, 4-2, and 4-3]. There was a predominant trend associated with the preliminary hypothesis particularly in the 3-1 task type comparison for time domain indices and the geometric derivatives.

Results from the age classification section support previous literature which indicates younger subjects have higher values of HRV at rest compared to older adults (Makivić et al., 2013). There is a prominent difference in HRV results for the different age classifications, which should be thought-out when specialized task programs are created in industrial settings.

Some prior studies have indicated that HRV does not successfully decipher changes in task demands; new conclusions have been obtained that demonstrate task demands can be categorized by HRV parameters (Mansikka et al., 2016). The results of this study support that Mean RR, SDNN, RR triangular index, and TINN all had significantly different corresponding means at least once during the simulated assembly line exercise.

In addition, the trend shown in Figure 3 is consistent with findings from a driver fatigue study that demonstrated LF/HF declines with the arrival of fatigue (Patel et al., 2011). Schmitt et al. (2015) highlighted the significance of frequency domain parameters while deciphering between different fatigue levels, while time domain indices are insufficient at presenting fatigue levels. The LF/HF trend in this study was representative of the increase in task fatigue, which is also demonstrated by the NASA TLX and subjective fatigue rating boxplots.

This study tested the SDNN and LF of 20 participants during an assembly line task to unfold the relationship ambiguity of these two parameters. Preceding literature has indicated that SDNN is highly correlated to LF (McCraty and Shaffer, 2015). However, enhanced understanding on the conditions needed to yield this significant correlation had to be further uncovered. This study displays a correlating trend for these two parameters while the participants were standing performing a dynamic task.

LIMITATIONS AND STRENGTHS

For future experiments, the time at which the experiment is executed should be controlled for each of the subjects participating in the study. A smoking verses non-smoking questionnaire would also benefit to assess the history and current smoking status for each subject. These two factors influence HRV outputs and should be closely monitored and controlled for. A total of three hours' worth of data was collected for each participant totaling approximately 13,000 data points per person. Future work should consider assessing more of the data points to evaluate the HRV parameters along the time series.

There is disagreement in the literature regarding what the HRV parameters reveal during work-related tasks. The current study had consistent results compared to studies of driver fatigue (Patel et al., 2011); however, other studies capturing HRV in a sports and physical setting indicate contradictory results (Makivic et al., 2013). The ambiguity across the literature gives complexity to interpreting HRV results. This study joins together objective and subjective measures to support previous findings in the HRV literature.

Overall, this study demonstrates the application of HRV analysis which can establish fatigue levels throughout the task. The study applies the use of HRV in a simulated assembly line task which allowed for the delineation of fatigue points during the entire assembly task. The repeatability for the heart rate monitor application was a key attribute in maintaining consistent data. This was controlled by having the same lab assistant apply the device on all of the participants making it possible to capture accurate measures.

CONCLUSION

In this work comparisons were made to current literature in exercise physiology to draw relationships between a simulated industrial task and HRV. The ANOVA analysis displayed significant differences for all the frequency domain parameters when the supine and standing positions were compared.

Midway into the task, several differentiating features were discovered for the time domains, specifically Mean RR, SDNN, and RR Triangular Index during the 3-1 and 3-2 task time comparisons. Gender was also a notable factor with decreased HRV for the male subjects in all areas except for HF. Future studies should further evaluate these trends to better understand the significant relationships HRV has with age, gender, and mental workloads.

REFERENCES

[1] Dong, J.-G. (2016). The role of heart rate variability in sports physiology. *Experimental and Therapeutic Medicine*, *11*(5), 1531–1536.

[2] Heart Rate Variability. (2001). Retrieved February 10, 2017, from https://www.heartmath.org/research/science-of-the-heart/.

[3] Mahmud, M., & Nafis, D. (2011). Study the Impact of Fatigue and Optimizing Productivity of an Assembly Line of Garment Industry. *International Journal of Scientific & Engineering Research*.

[4] Makivić, B., Djordjević Nikić, M., & Willis, M. S. (2013). Heart rate variability (HRV) as a tool for diagnostic and monitoring performance in sport and physical activities. *Journal of Exercise Physiologyonline*, *16*(3), 100-109.

[5] Maman, Z. S., Yazdi, M. A. A., Cavuoto, L. A., & Megahed, F. M. (2017). A data-driven approach to modeling physical fatigue in the workplace using wearable sensors. *Applied Ergonomics*.

[6] Mansikka, H., Virtanen, K., Harris, D., & Simola, P. (2016). Fighter pilots' heart rate, heart rate variation and performance during an instrument flight rules proficiency test. *Applied ergonomics*, *56*, 213-219.

[7] McCraty, R., & Shaffer, F. (2015). Heart Rate Variability: New Perspectives on Physiological Mechanisms, Assessment of Self-regulatory Capacity, and Health risk. *Global Advances in Health and Medicine*, *4*(1), 46–61. http://doi.org/10.7453/gahmj.2014.073

[8] Medeia. (1988-2017). Autonomic Nervous System Testing- ANS Testing Retried. Retrieved January 12, 2017, from http://www.qhrv.com/dtr_ans.htm

[9] Patel, M., Lal, S. K. L., Kavanagh, D., & Rossiter, P. (2011). Applying neural network analysis on heart rate variability data to assess driver fatigue. *Expert systems with Applications*, *38*(6), 7235-7242.

[10] Ravé, G., & Fortrat, J. O. (2016). Heart rate variability in the standing position reflects training adaptation in professional soccer players. *European journal of applied physiology*, *116*(8), 1575-1582.

[11] Schmitt, L., Regnard, J., & Millet, G. P. (2015). Monitoring Fatigue Status with HRV Measures in Elite Athletes: An Avenue Beyond RMSSD?. *Frontiers in physiology*, *6*, 343.

[12] Yijing, Z., Xiaoping, D., Fang, L., Xiaolu, J., & Bin, W. (2015). The effects of guided imagery on heart rate variability in simulated spaceflight emergency tasks performers. *BioMed research international*, *2015*.

[13] Zhang, J. (2007). Effect of age and sex on heart rate variability in healthy subjects. *Journal of manipulative and physiological therapeutics*, *30*(5), 374-379.