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Evaluation of Subjective Workload Using NASA-TLX and Heart Rate in Order-picking Operations

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Abstract

In recent years, the increase in "staying at home and spending" and the expansion of the e-commerce market due to the spread of COVID-19 have led to a serious labor shortage in the logistics industry as a whole. Therefore, it is expected to promote the employment of elderly and female workers as potential labor force, and to create a comfortable working environment that takes into account the burden on workers. The purpose of this study is to evaluate the burden on workers who perform order picking, which is the core of the supply chain, from both physiological indices and subjective workload, and to clarify the correlation between these two indices. Furthermore, we estimate the values obtained by the subjective workload evaluation method from physiological indices with high correlativity. In the present study, we conducted an experiment that reproduced the order-picking process in an actual logistics warehouse. The NASA-TLX was used as the subjective burden evaluation method, and the Poincaré plot, a type of heart rate variability analysis, was used as the objective burden evaluation method. As a result, the combination of the burden indices of the Poincaré plot and the burden factors of NASA-TLX that showed significant correlations were m and physical demands, σ_{-x} and time demands.

Keywords: Behavioral Science, Logistics, Poincaré plot, Wearable Device

1 Introduction

In recent years, a reduction in opportunities for human contact has been recommended as a countermeasure to COVID-19 expansion. Staying at home and spending—in which ordering, purchasing, and consumption of products are completed at home—have increased. Additionally, the expansion of the e-commerce market and diversification of products have drawn attention to the efficiency of the entire supply chain and the way it works [1]. Distribution warehouses, which are located between manufacturers (factories) and retailers, are at the core of the supply chain, and improving the efficiency of these warehouses is important in improving the efficiency of the entire supply chain. Logistics robots have a considerable impact on the efficiency of warehouse operations. The market size of logistics robots is expanding to the extent that it is expected to increase eight-fold by 2030 compared with 2020 [2], and it is necessary to consider improving efficiency in a work environment where robots and humans coexist.

In warehouse operations, order-picking is the most time-consuming and costly task [3]. Therefore, many logistics robots have been introduced to improve the efficiency of order-picking operations. Conventional picking requires the worker to “move” or “search” to the shelf where

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the specified product is stored, and most of the work time in order-picking operations is this moving time [4]. Shelf-transfer robots can eliminate the transfer time. The shelf-transfer robot moves the storage rack to the work area where the worker is located. A worker does not need to move or search. The introduction of shelf robots eliminates the need to move and search from the picking process, and the time spent can be used to remove and inspect items, resulting in a significant improvement in work efficiency. There have been many opportunities to focus on improving logistics efficiency but few opportunities to focus on human factors such as the physical burden on workers. In the U.S., the annual economic burden of work-related musculoskeletal disorders is estimated to be $45–$54 billion USD [5], and the impact on economic losses, such as worker absenteeism and compensation issues, needs to be emphasized.

One method for evaluating the burden on workers is a subjective burden evaluation using questionnaires. Although this method has the advantage of clarifying the factors that workers find burdensome, it also has the disadvantage of taking time to answer and tally the answers. However, there is a method to determine the burden on workers using physiological indicators. This method uses the characteristic that the endocrine and autonomic nervous systems are affected when the human body is subjected to physical and mental stress. It has the advantage of enabling inexpensive and noninvasive measurement when analyzing heartbeat, respiration, brain waves, and so on. In recent years, with the spread and improved performance of wearable devices, the ability to easily obtain biological data has also become a major advantage. Therefore, the purpose of this study was to evaluate the burden on workers from both physiological indices and subjective workload assessment and to estimate the value obtained by the subjective workload assessment method from the physiological indices by confirming the correlation between the two. In this study, heart rate was used as a physiological index, and the NASA task load index (NASA-TLX) [6] was used as a subjective workload assessment method.

2 Literature Review

There are several studies analyzing the relationship between subjective mental workload assessment and objective burden assessment. Digiesi et al. [7] propose an analytical model to estimate the cognitive workload of workers. They have subjects perform standard tasks with different cognitive loads. They use the NASA-TLX test as a subjective assessment measure and heart rate variability as an objective indirect measure of workload. For the measurement, subjects have pre-gelled electrodes affixed to their chests. Soga, Miyake, and Wada [8] had the workers per-form mental tasks and change their emotions to clarify the relationship between physiological responses and emotional changes. Healthy male graduate students were asked to perform calculation tasks of varying difficulty, and various autonomic nervous system indices were measured, as well as subjective workload, mood, and feelings toward the tasks. They measured ECG, Blood Pressure, Photoelectric Plethysmogram, Tissue Blood Volume, Skin Potential Level, and Cardiac Output as objective evaluation indicators. However, the Skin Potential Level, a type of electrodermal activity, may have been influenced by emotions such as anxiety about the measurement itself. The gelatinized electrodes in the studies by Digiesi et al. [7] were also similar. The electrode attached to the chest may cause anxiety or discomfort to the subject. In this study, a wearable heart rate monitor, which is more non-invasive than electrodes, was used to reduce anxiety and discomfort during measurement. The wearable heart rate monitor is characterized by its ability to measure in real time, and does not require time as is the case with questionnaire surveys. In this study, a wearable heart rate monitor, which is more non-invasive than electrodes, was used to reduce anxiety and discomfort during measurement. The wearable heart rate monitor is characterized by its ability to measure in real time, and does not require time as is the case with questionnaire surveys.

Alaimo et al. [9] analyzed the relationship between workload and fatigue in aircraft pilots for the purpose of human error prevention. They performed qualitative and quantitative correlation analysis between the error index and subjective and objective measures. They used the NASA-TLX as a subjective evaluation index and heart rate variability as an objective evaluation index. The work was conducted in the cockpit, a small workspace simulator, with the flight segments of the takeoff and landing phases as the subjects of the experiments. The "ratio of the high-frequency component LF to the low-frequency component HF" was calculated from the heart rate variability, and an index representing the balance between the sympathetic nervous system working during loading and the parasympathetic nervous system working during rest was used as one of the evaluation indices. However, this index requires a relatively long period of heart rate data. In addition, complex calculations such as fast Fourier transforms are required for frequency analysis. Therefore, in this study, the Poincaré plot [10] of geometric figure analysis is used for heart rate variability analysis. To explain the Poincaré plot, we discuss the RR interval (RRI) and the R wave; the R wave is a waveform indicating myocardial excitation and ventricular contraction. It is called an R wave because it appears as a waveform showing positive maxima as the heart's electrical signals pass through the ventricles. RRI is the interval between R waves in the ECG waveform. RRI is an indicator of physical and mental stress [11]. The data acquired in this study are the RRI shown in Figure 1, which is the interval between the R waves and the largest waves in the electrocardiogram waveform.

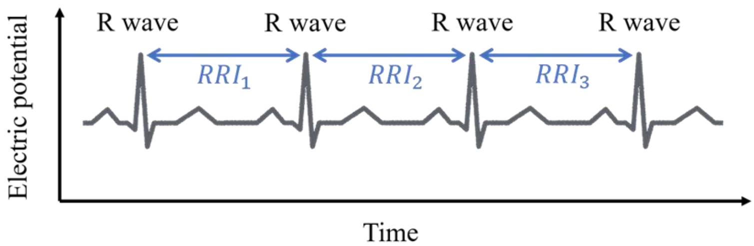

Figure 1: Conceptual diagram of the RR interval

A Poincaré plot is one in which the RRI is obtained, the RRI in k is plotted on the horizontal axis, and the RRI in $k+1$ is plotted on the vertical axis. It is an autonomic function test that uses an electrocardiogram and is a useful method to visually capture RRI fluctuations [10]. Figure 2 shows the evaluation method for the Poincaré plot. All points plotted in the Poincaré plot were projected onto the $y = x$ and $y = -x$. After projection, on the $y = -x$, the mean of the distances (on the $y = -x$) from the origin $(0, 0)$ is m, and the standard deviation of the distances from the origin $(0, 0)$ is σ_x. The standard deviation of the distance from the origin $(0, 0)$ on the $y = -x$ is σ_{-x}, and the area of the ellipse with σ_x as the major axis and σ_{-x} as the minor axis is S.

$$S = \pi \times \sigma_x \times \sigma_{-x}$$

The quadruple standard deviations of the ellipse in the direction of the major and minor axes are L and T, and L/T is used as another index of burden [10].

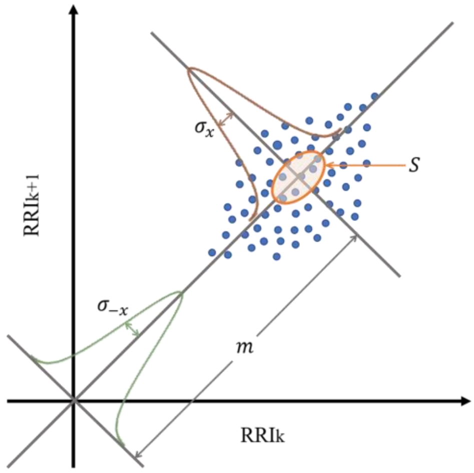

Figure 2: Description of the Poincaré plot

However, the evaluation indices S and L/T in previous studies include a standard deviation σ_x in the long axis direction, and the length of the long axis represents the change in heartbeat interval throughout the experiment. The standard deviation in the direction of the major axis varies depending on the experimental conditions and experimental design. The length of the major axis is expected to be larger when multiple tasks or various tasks are mixed in the overall experiment. The length of the major axis may not be able to cope with the variable nature of the picking task, the subject of this study, which is a mixture of active tasks, such as crouching and walking, and resting tasks, such as waiting. Therefore, in this study, the length of the minor axis, σ_{-x}, is used as a new index to evaluate the burden. The RRI fluctuation of σ_{-x}, which indicates the fluctuation of the heart rate, is characterized by the fact that the RRI fluctuates more when the subject is at rest and less when the subject is under strain. From σ_{-x}, a new burden measure, we estimate the value obtained by the subjective burden assessment method NASA-TLX.

3 Burden Detection by NASA-TLX

3.1 Description of the NASA-TLX

NASA-TLX is a subjective mental workload assessment method that has been used in many recent studies [12]. NASA-TLX has six evaluation scales (or subscales) for the target task:

- Mental demands: How much intellectual and perceptual activity (thinking, deciding, calculating, remembering, seeing, etc.) are required? Was the task easy or difficult, simple or complex, and precise or rough?
- Physical demands: How much physical activity is required (pushing, pulling, turning, controlling, moving around, etc.)? Was the work easy or hard, slow or fast, and restful or strenuous?
- Temporal demands: How much time pressure did you feel owing to the pace of work and the frequency of assignments? Was the pace slow and leisurely or fast and rushed?
- Operation performance: How well do you think you met the goals of the assignment set by the work leader (or yourself) and how satisfied are you with your performance concerning meeting the goals?

- Effort: How much mental and physical exertion did you have to exert to achieve and maintain your level of work performance?
- Frustration: How anxious, discouraged, irritated, stressed, or worried did you feel during work? Conversely, to what extent did you feel relieved, satisfied, content, happy, or relaxed?

For each of these six subscales, a burden rating (0–100) was assigned, with low–high or good–bad as the extremes. The importance of the six subscales was then judged by pairwise comparisons. Since the six scales can be combined into 15 pairs, participants made 15 comparative judgments, and the number of times they selected each scale as "more important" was counted as the weight of each scale [13]. If the number of times each subscale is selected (0–5) is set as the weight coefficient w_i for that scale, and the rating value of each subscale is set as v_i, the weighted average workload score (WWL), which is the workload evaluation index of the task, is calculated as follows, with values ranging from 1 to 100:

$$\mathrm{WWL} = \frac{\sum_{i=1}^{6}(w_i \times v_i)}{\sum_{i=1}^{6} w_i}$$

However, the definition of mental workload has not been unified [14]. Therefore, in this study, mental workload was defined as "mental workload/burden," as in Shimojo et al. [15]

3.2 Application of the NASA-TLX to Burden Surveys

Because the NASA-TLX is a subjective mental workload assessment method, it is essentially an index for evaluating the mental workload and burden of workers. However, Miyake, Kumashiro, Murakami, and Sasaki [16] applied the NASA-TLX to a survey of workers' sense of workload at a manufacturing site. This is because manufacturing work is not entirely free of mental factors, and the NASA-TLX has a subscale for physical burden. Miyake et al. showed that the sensitivity of the NASA-TLX was high for this subscale; although, they did not find good sensitivity to the WWL. Therefore, in this study, the NASA-TLX was used as a subjective burden assessment method, as described by Miyake, Kumashiro, Murakami, and Sasaki [16].

4 Experiment

An experiment that reproduces a picking operation was conducted with reference to an actual logistics warehouse work site.

4.1 Application of the NASA-TLX to Burden Surveys

Product shelves containing cardboard boxes with dummy products were set at three different heights: lower, middle, and upper. The height of each shelf was set to 30, 90, and 150 cm from the ground to reproduce the shelves with the highest number of units in an actual distribution warehouse used as a reference in this study. The total weight of the products and cardboard boxes containing the products was 1.85 kg. The participant was a man in his 20s, 170 cm tall, standard build, free from disease, and a healthy nonsmoker. A height of 90 cm from the ground for the middle shelf is the height at which a worker can take out cardboard boxes from within the normal work area. It is recommended to work within a normal work area for time efficiency and to reduce physical burden [17]. Therefore, it is presumed that the work at the middle height in this experiment places less of a burden on the operator than the upper and lower heights that are not within the normal work area.

4.2 Experimental Contents

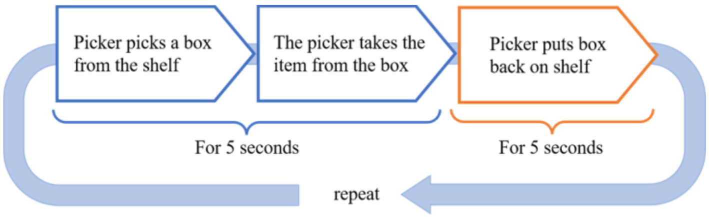

Figure 3: Details of operations in this experiment

This study reproduced part of a picking operation at a site where a shelf-transfer robot was installed. The experiment lasted for three days, and the robot performed the upper, middle, and lower picks three times per day for nine picks per day. The work contents are shown in Figure 3. These two operations were continued for five minutes. The duration of each five-second task was set based on the average duration of the corresponding part of the task at an actual company's work site.

4.3 Reproducibility and Validity

The reproducibility and validity of using the NASA-TLX as a subjective burden assessment method are shown in the same way as in Miyake, Kumashiro, Murakami, and Sasaki [16]. Table 1 shows the results of the NASA-TLX for nine tasks in three sessions.

Table 1: NASA-TLX Results

		Mental demands	Physical demands	Temporal demands	Operation performance	Effort	Frustration	Weighted average workload score
*	Upper row	0.00	23.33	18.67	2.33	8.67	11.00	64.00
	Middle row	0.00	*18.33*	*17.33*	2.00	*8.00*	5.33	*51.00*
	Lower row	0.00	25.00	*17.33*	2.33	10.00	6.67	61.33
**	Upper row	0.00	16.00	21.67	1.67	8.00	12.00	59.33
	Middle row	0.00	*8.00*	*16.67*	2.33	*2.67*	5.33	*35.00*
	Lower row	0.00	25.00	18.67	2.00	14.00	8.67	68.33
***	Upper row	0.00	23.33	8.00	1.67	17.33	12.00	62.33
	Middle row	0.00	*9.33*	*6.00*	1.33	*4.00*	13.33	*34.00*
	Lower row	0.00	28.33	9.33	1.67	21.33	14.00	74.67

* First session, ** Second session, *** Third session

First, the correlation coefficients of all NASA-TLX rating scales for all tasks in each session were examined in the test-retest for reproducibility. The correlation coefficients were $r = 0.9599$ for the first and second sessions, $r = 0.9118$ for the first and third sessions, and $r = 0.9472$ for the second and third sessions (all $p < .001$).

Next, we examine the validity of our results. Within the normal work area, workers can perform their work according to the laws of nature, and the system is designed so that there is not a burden on the worker [17]. The middle work is less burdensome than the upper and lower work because it can be completed within the normal work area. Figure 4 shows the average of the evaluation values of all three subscales and the WWL for each step. The evaluation values of the subscales, except for the operation performance of middle work, are lower than those of upper and lower work. This indicates the effectiveness of using NASA-TLX as an evaluation of workload.

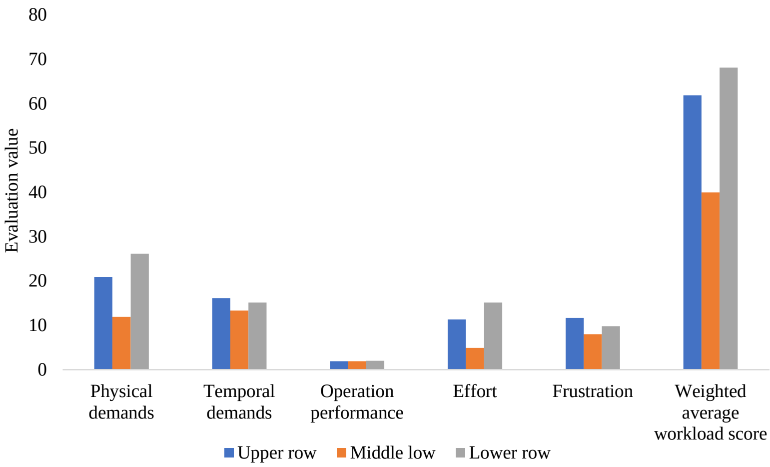

Figure 4: Average of the NASA-TLX ratings

4.4 NASA-TLX Results

Table 1 shows that the weight of the intellectual and mental demands was zero for all nine tasks, probably because the content of this task did not include elements such as thinking, calculating, and memorizing, and the evaluation value was zero. When we focused on the physical demands, the middle, upper, and lower rows had the highest values in all sessions, in that order. In addition, the middle row had the lowest values for time pressure, effort, and WWL, which is the overall evaluation value, as expected because the middle row, which is within the normal working range, has the lowest burden on the worker.

5 Burden Detection Using a Wearable Device

5.1 Device Used

The wearable device used in this study was a Polar H10 wearable heart-rate monitor(Polar H10; Polar Electro Oy, Kempele, Finland). The device was attached to the participant's chest with a cloth chest strap that wraps slightly below the chest and adheres closely to the skin. The device is used by medical researchers and professional athletes because it is free from interference, even when the participant moves their body. The device can also be connected to a smartphone via Bluetooth for real-time data transmissions.

5.2 Poincaré Plot Results

Figure 5 plots the experimental data in the first middle stage work when the experiment was conducted in the environment and content of Section 3.1 and 3.2. Shading of the points represents the frequency. Usually, Poincaré plots are elliptically distributed, with the straight line "$RRI(k+1) = RRI(k)$" as the major axis. We confirmed that the distribution was elliptical in all nine sets of data.

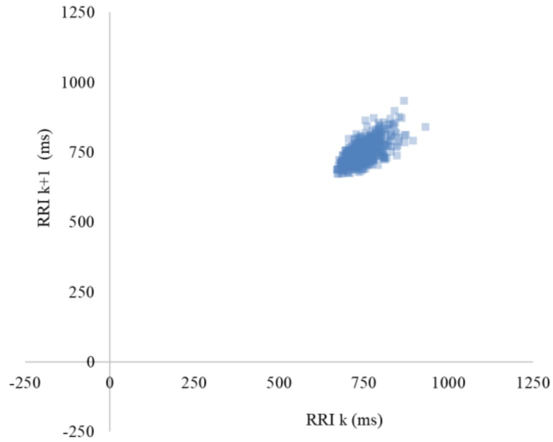

Figure 5: Example of Poincaré plot

5.3 Average Distance m and Elliptical Area S

Toyofuku, Yamaguchi, and Hagiwara [18] showed that parasympathetic activity is significantly correlated with two indices: mean distance from the origin, m, and ellipse area, S. higher values of m and S indicate more active parasympathetic activity; that is, a relaxed state. Table 2 shows that the middle row had the highest value of m at all times, followed by the upper row and the lower row. Next, for S, because the middle row, which is within the normal working range, is considered to have the lowest burden, it was assumed that S would have the largest value in each session; however, in the first session, the middle row had the smallest value and the results varied.

5.4 L/T

The ratio of L to T, L/T, which is the quadruple value of the standard deviation in the direction of the major and minor axes of the ellipse, has a larger value in the resting state and a smaller value in the stress/strain state [10]. From the results in Table 2, it was inferred that L/T would have its maximum value in the middle row because the middle row, like S, is considered the least burdensome task. The results for m shown above indicate that the middle row is the least burdensome task. However, because the results for S and L/T varied, the correlation with the subjective burden rating determined which metric should be used.

Table 2: Results for all burden indicators

		m	S	L/T	σ_{-x}
First session	Upper row	1027.58	2978.67	5.35	13.31
	Middle row	*1064.30*	2780.88	3.57	15.74
	Lower row	880.74	2885.38	4.02	15.12
Second session	Upper row	997.65	1208.08	4.60	9.15
	Middle row	*1050.45*	1404.36	3.27	11.69
	Lower row	862.41	1398.71	4.77	9.66
Third session	Upper row	962.39	2563.56	5.69	11.97
	Middle row	*990.48*	2755.47	4.67	13.71
	Lower row	825.72	2884.79	2.95	17.64

5.5 Correlation Between Poincaré Plot and NASA-TLX

The results of the evaluation indices obtained from the Poincaré plot were compared with those of the NASA-TLX, a subjective evaluation index. This is consistent with the results of the average distance from the origin (m) of the three evaluation indices obtained from the Poincaré plots. Contrastingly, the results for the area of ellipses S and L/T are different from those obtained using the standard deviation in the direction of the major and minor axes of the ellipse. Correlations between the Poincaré plots and six NASA-TLX subscales were examined. The results are presented in Table 3. The m scores were strongly negatively correlated with physical demands, effort, and WWL. m correlated with these three subscales (p < .05). The σ_{-x} scores were strongly negatively correlated with Temporal demands, and Operation performance. σ_{-x} correlated with these two subscales (p < .05). No strong correlations were found for S and L/T in any of the scales. Based on these results, heart rate variability data can reveal some burden factors by m and σ_{-x}. No strong correlations were found for S and L/T in any of the scales. Based on these results, m was determined as the evaluation index to be used when evaluating the subjective workload of workers based on the heart rate variability.

Table 3: Correlation coefficients between indices obtained from Poincaré plots and NASA-TLX subscales and overall evaluation values

	Physical demands	Temporal demands	Operation performance	Effort	Frustration	Weighted average workload score
m	*-0.70*	0.21	0.15	*-0.74*	-0.34	*-0.67*
S	0.37	-0.49	-0.04	0.25	0.20	0.15
L/T	0.12	-0.05	-0.16	0.03	0.35	0.14

σ_{-x}	-0.13	*-0.74*	*-0.68*	0.13	0.63	-0.17

5 Evaluation of Subjective Workload Using Heart Rate Variability Data

5.1 Derivation of Regression Line Between m and NASA-TLX Valuations

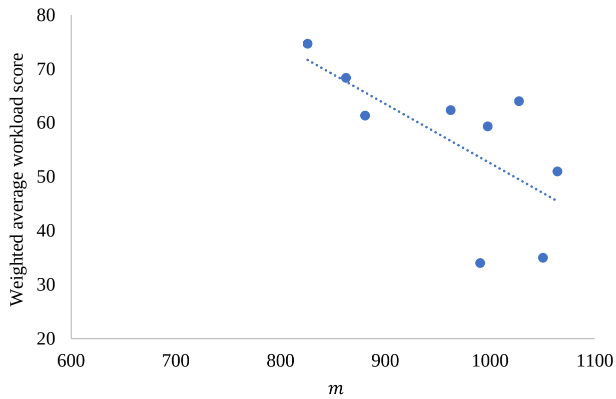

Figure 6: Scatter plot of m and weighted average workload score

In the results of the correlation between the index and NASA-TLX using the Poincaré plot in Table 3, we focus on the three evaluation values of physical demands, effort, and WWL, which showed a significant correlation. Figure 6 shows the scatter plot and regression line between the WWL and m. The regression lines for m and each parameter were as follows:

$$\text{Physical demand: } y = -0.0585x + 75.944$$

$$\text{Effort: } y = -0.0523x + 60.761$$

$$\text{WWL: } y = -0.1097x + 162.27$$

5.2 Prediction of Subjective Work Burden

The first and second experiments were conducted in the same environment, under the same conditions, and on a different worker to obtain heart rate variability data and NASA-TLX response results. Another participant was a woman in her 20s, 147 cm tall, free of disease, and a healthy nonsmoker. The obtained heart rate variability data were plotted elliptically using a Poincaré plot, and the average distance from the origin (m) was calculated as an evaluation index. m is 783.28, 938.71, and 867.30 in the order of upper, middle, and lower in the first session, and 775.89, 905.83, and 861.27 in the order of upper, middle, and lower in the second session. Based on m, the predicted values of the three evaluation measures of the NASA-TLX, physical demands, effort, and WWL, were calculated and compared with the measured values. The results are presented in Table 4. A large discrepancy between the predicted and measured values was observed in the middle of the first session for physical demands, in the lower part of the first session for effort, and in the upper part of the first and second sessions for WWL. This is thought to be owing to differences in physical characteristics, such as sex and height differences, as well as differences in mental characteristics in how the rating values of the subscales of the subjective burden evaluation were assigned and weighting was appropriately selected. However, the residuals for the other parameters were sufficiently small, even though participants had a height difference of 20 cm or more and a sex difference. This result indicates the validity of predicting subjective burden based on the physiological index of the heart rate.

Table 4: Predicted Results of the NASA-TLX

		Physical demands			Effort			Weighted average workload score		
		PV	MV	R	PV	MV	R	PV	MV	R
*	Upper row	30.12	31.67	1.54	19.80	17.00	2.80	76.34	88.33	*11.99*
	Middle row	21.03	8.67	*12.36*	11.67	9.00	2.67	59.29	57.00	2.29
	Lower row	25.21	25.00	0.21	15.40	9.33	*6.07*	67.13	65.00	2.13
**	Upper row	30.55	26.67	3.89	20.18	19.00	1.18	77.15	92.00	*14.85*
	Middle row	22.95	26.67	3.71	13.39	15.00	1.61	62.90	69.33	6.43
	Lower row	25.56	25.00	0.56	15.72	15.00	0.72	67.79	65.67	2.12

* First session, ** Second session, PV is Predicted value, MV is Measured value, R is Residual

6 Conclusion

In this study, we evaluated subjective workload using heart rate variability data. The accuracy of the assessment was confirmed using heart rate variability data from workers of different sexes and physical characteristics. Consequently, significant correlations were confirmed between physical demands and effort, which are subscales of the NASA-TLX and WWL, which is an overall evaluation value. The validity of the estimation was confirmed even among participants with large differences in physical characteristics, such as sex and height. Concerning future tasks, the number of participants in this study was two, and the number of tasks was insufficient, which may have biased the results. Therefore, it is necessary to conduct experiments with a sufficient number of participants and tasks to confirm the correlation between the heart rate variability data and the subjective burden evaluation method. Another issue to be addressed is finding indices that can confirm significant correlations among items related to mental burden, such as intellectual and mental demands and frustration, for which no significant correlations were found in the present experiment. Consequently, we should be able to determine detailed factors of work burden and contribute to improving the burden of workers in actual workplaces.

Acknowledgement

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