EVALUATION OF FORCE REQUIREMENTS AND POSTURE IN MANUAL COFFEE HARVESTING

by:

Ambar G. Rodríguez Vélez

A thesis submitted in fulfillment of the requirements for the degree of:

MASTERS OF SCIENCE

in

INDUSTRIAL ENGINEERING

UNIVERSITY OF PUERTO RICO

MAYAGÜEZ CAMPUS

2018

Approved by:

__________________________ ____________________

Cristina Pomales García, PhD Date
President, Graduate Committee

__________________________ ____________________

Maria de los A. Irizarry., PhD Date
Member, Graduate Committee

__________________________ ____________________

Francisco M. Monroig Saltar, PhD Date
Member, Graduate Committee

__________________________ ____________________

Rocío Zapata Medina, M.S. Date
Representative of Graduate Studies

__________________________ ____________________

Viviana I. Cesaní, PhD Date
Chair, Department of Industrial Engineering

ABSTRACT

Manual coffee harvesting is a common agricultural task, used around the world, with the potential risk for the development of Musculoskeletal Disorder (MSD). This research evaluates the hand and wrist biomechanical risks that workers undergo while harvesting coffee using two manual methods: selective picking and scraping. To evaluate the biomechanical risks associated with the possibility of developing MSDs, the research employed qualitative and quantitative methods such as an adapted Nordic Questionnaire, Rapid Upper Limb Assessment (RULA), Hand Activity Level (HAL) and Regression Analysis. The qualitative assessment results showed that 43% of the sample reported experiencing pain in the hands and wrists in the previous year. This result was related to the findings from the RULA postural analysis, where 60% of the cases, out of 21 evaluations, reflected that the task should be evaluated more thoroughly and changed soon or immediately. In addition, the RULA evaluation evidenced the need to include: tree height, use of a harvesting basket and harvesting method as relevant variables in the postural analysis. The quantitative analysis demonstrated empirical evidence of finger grip and pinch forces between 0.006 N and 21 N in both harvesting methods studied. Also, HAL results suggest that the task has a risk potential for developing MSDs, as exertion forces and frequency of movements showed that 82% of the sensors with highest force activity resulted in hand activity levels above the desired Action Limit for the selective method in comparison to 38% of sensors during the scraping method. Finally, the regression analysis used to predict hand forces, using the qualitative factors and Principal Component Analysis to reduce model complexity, was not appropriate to model the hand forces data obtained from the field study.

RESUMEN

La recolección manual de café es una tarea agrícola común, utilizada en todo el mundo, con el riesgo potencial de desarrollar desórdenes musculo-esqueletales (DTA). Esta investigación evalúa los riesgos biomecánicos de la mano y la muñeca que experimentan los trabajadores mientras cosechan el café usando dos métodos manuales: selección selectiva y raspado. Para evaluar los riesgos biomecánicos asociados con la posibilidad de desarrollar DTA, la investigación empleó métodos cualitativos y cuantitativos, tales como un cuestionario nórdico adaptado, evaluación rápida de miembro superior (RULA), nivel de actividad de mano (HAL) y análisis de regresión. Los resultados de la evaluación cualitativa mostraron que el 43% de la muestra informó haber experimentado dolor en las manos y muñecas el año anterior. Este resultado se relacionó con los hallazgos del análisis postural RULA, donde el 60% de los casos, de 21 evaluaciones, reflejaba que la tarea debería evaluarse más a fondo y cambiarse pronto o inmediatamente. Además, la evaluación RULA evidenció la necesidad de incluir: la altura del árbol, el uso de una cesta de recolección y el método de cosecha como variables relevantes en el análisis postural. El análisis cuantitativo demostró evidencia empírica de fuerzas de agarre con los dedos entre 0.006 N y 21 N en ambos métodos de cosecha estudiados. Además, los resultados de HAL sugieren que la tarea tiene un riesgo potencial de desarrollar DTA, ya que las combinaciones de fuerzas y la frecuencia de movimientos demostraron que el 82% de los sensores con mayor actividad de fuerza resultaron con niveles de actividad manual superiores al límite de acción deseado para el método selectivo en comparación al 38% de los sensores durante el método de raspado. Finalmente, el análisis de regresión utilizado para predecir las fuerzas de la mano, utilizando los factores cualitativos y el análisis de componentes principales para reducir la complejidad del modelo, no fue apropiado para modelar los datos de las fuerzas de mano obtenidas del estudio de campo.

ACKNOWLEDGEMENTS

I would like to thank God and my family for being a support system throughout this journey. I extend my gratitude to my thesis committee Cristina Pomales-García, Francisco M. Monroig Saltar, and María de los A. Irizarry, for their guidance and mentoring throughout these years. Also, professor Noel Artiles, for his guidance and support in the data analysis, and undergraduate student Johana Mercado. I would also like to extend my gratitude to the personnel at the Agricultural Experiment Station in Adjuntas for their collaboration. Finally, I would like to extend my gratitude to my friends, who encouraged me throughout the years.

This journey would not have been possible without the voluntary work of the different participants and coffee farm owners who opened their farms for the research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

According to the International Coffee Organization (2018), approximately 70 countries around the world produce coffee, with fifty-two of these countries employing about 26 million people. In Puerto Rico, the coffee industry remains in the first ten agribusinesses of importance in the economy. Since 2011, the contribution to the economy has diminished significantly according to the preliminary report of the Total Gross Income of Agriculture in Puerto Rico (Flores Ortega, 2011). The factors influencing this decrease include the labor shortage, increase in production costs, coffee borer beetle (*Hypotenemus hampei)* plague*,* and shortage of government support to this industry. In 2007, it was estimated that during the harvesting season, the coffee industry employed between 10,000 to 13,000 workers from the central area of Puerto Rico.

Coffee harvesting season in Puerto Rico begins in the month of August in the low-altitude zones and ends in the month of February in the high-altitude zones. Since there are several flowering periods during the year, coffee fruits do not ripen at the same time, therefore its harvesting requires a distinction between ripe and unripe fruits from the tree, leaving the unripe ones to harvest them later on in the season (Monroig Inglés, n.d.). Although there are devices or machinery to help in the coffee harvesting, most of the time the harvest is done by hand. There are various manual methods for collecting coffee, but most of them require the use of both hands and repetitive movements of the upper body. One manual method is hand picking the ripe coffee fruit individually by twisting it off the branch and depositing it in a basket. It is common for workers to suspend the harvesting basket around their waist, shoulders, necks or on the floor. Another method consists in scraping the branch, removing both mature and green fruits, and depositing them in the basket. This last method is not recommended since it causes damage to the coffee tree and affects negatively the next harvest. However, due to the labor shortage, it is commonly used in Puerto Rico.

One of the issues in manual labor is the incidence of work-related injuries. According to Davis and Kotowski (2007), around 160 million work-related injuries occur per year in the world. During 2013, around 13,850 work-related injuries and diseases were reported in Puerto Rico from which 2,920 cases involved repetitive movements. In particular, the incidence rate for work related injuries reported by the agricultural sector was of 0.1 (Department of Labor and Human Resources, 2015). Due to Occupational Safety and Health Administration federal recordkeeping requirements (Occupational Safety and Health Administration & Department of Labor, n.d.), this data does not include injury or illness information from farms with less than 11 workers and family owned businesses. This evidence suggests that coffee harvesters could be at risk for developing musculoskeletal disorders due to the repetitive movements of their work and given the federal record keeping requirements, the data available through the Department of Labor may underestimate the rate of work related injuries.

The following chapter will provide an in-depth literature review focusing on studies that evaluate work related injuries in agriculture by body area, as well as common evaluation tools, and research methodologies.

2 LITERATURE REVIEW

Different studies have exposed the effects of agricultural jobs on the human body, including Musculoskeletal Disorders (MSD). Naeini, et al. (2014), documented an approach to prevent work related MSD’s, highlighting the ergonomic problems in the agricultural industry. Their research found that ergonomists are capable of providing a safer work environment for agricultural workers in developing and developed countries. In a previous literature review (Davis & Kotowski, 2007), researchers concluded that agricultural workers in the United States are faced with many work related injuries. The following sub sections describe the research findings related to evaluation and impact of ergonomic research, focusing on lower back, lower extremities, upper back, upper extremities, and hands.

2.1 Impact of Ergonomic Research by Body Area

Commonly, ergonomic research and interventions in agriculture focalize on the effects on the back and legs. For example, Jin, McCulloch and Mirka (2009) studied the biomechanical responses of the lower back during a harvesting task, alternating different postures of workers assumed during pepper harvesting. They found that an intervention consisting of a knee support, was outweighed by reduced productivity and a high degree of trunk flexion, and that the current approach of alternating between various postures during harvesting may be the best strategy.

With respect to the upper body, researchers have studied ergonomic risk factors in agricultural tasks associated with harvesting apples, coffee and tea. Thamsuwan, Aulck, Galvin, & Johnson (2014), analyzed the postural and upper arm impacts of apple harvesting. In their study, the impact of a new mobile platform was compared to conventional ladders. They also developed and evaluated computational methods for characterizing repetitive motions in the arms and shoulders from data continuously collected from the field. Their findings showed that the use of a platform reduced fatigue in the upper arms in two subgroups of workers. As in many harvesting activities, it was also observed that repetition rates for the upper arm were high for both methods studied.

Bao et al. (2013) studied the effects of the large and small baskets used for collecting coffee in Nicaragua, and a newly developed bag. Electromyography (EMG) and questionnaires were used to assess the physical hazards. The data obtained from different activities, which was normalized and analyzed, proved statistical significance for lifting the 60 kg coffee transportation sack. When comparing the activities of dumping the coffee fruit and the coffee picking, dumping the coffee fruit proved to have higher statistically significant EMG levels ($p\text{-value} < 0.05$) for the right erector spinae, left trapezius and right erector spinae muscle. With the newly developed bag, the muscle load on the right erector spinae was significantly reduced.

Other studies in tea leaf plantation studied the ergonomic risk factors of women due to the activities performed in the plucking operation, which include highly repetitive movement (Bhattacharyya & Chakrabarti, 2012). These issues were quantified using the Occupational Repetitive Assessment (OCRA) and the Quick Exposure Check (QEC). Both, the OCRA index and the OCRA checklist indicate high risk in the plucking activity. They observed that the highest QEC scores were for the back and neck, 88.88% and 88.23% respectively, while for the wrist the score was 73.3%. Also, they suggested there is a strong evidence of awkward wrist/hand posture as a risk factor for the development of wrist disorders.

Biddle (2013) intended to “reduce occupational related injuries, illnesses fatalities and exposures by including prevention considerations in all designs that affect individuals in the occupational environment”. Biddle evaluated three business cases utilizing Prevention through Design (PTD) method. One of the business cases evaluated an “Ergonomic Wine Grape Picking

Tub" (Duraj et al., 2000), which consisted in changing the tub used to collect the grape clusters in a multistep process similar to the coffee harvesting process. The ergonomic risk factors identified by Duraj et al. (2000) where: high repetitive gripping, sustained trunk flexion for several seconds for every cycle (forward bend of 20º and subsequent 90º forward bend), contact stresses in hands and high metabolic demands. They found that the probability of back injury with the smaller tubs was reduced to 6% from an initial probability of injury of 64%. Also, the decrease in the weight of the tubs, from 57 pounds (25.7 kg) to 46 pounds (20.9 kg), reduced a post-harvesting pain score between the pre-intervention and post-intervention years. In this case, the results presented were an improvement in ergonomic risk factors. As part of their research, they found an increase in workers' satisfaction due to the decrease of the pain and discomfort was more important to the managers than the additional annual expenses. In addition, the productivity using smaller tubs apparently did not decrease since the workers did not experience a loss in wages. In contrast from the intervention proposed by Jin, McCulloch and Mirka (2009), reducing tub size was beneficial to the companies' business objective. In this context, business case developers should not lose sight of the need to capture information that is meaningful for the project investor or decision maker.

A meta-analysis focusing on prevention of work related MSDs (WRMSD's) in agriculture (Naeini et al., 2014) highlighted the ergonomic problems in the agriculture industry by analyzing nine different articles. In the cited work "An Ergonomic Approach to Citrus Harvest Mechanization" the manual and semi-mechanized fruit removing process were compared using a stopwatch technique. The study, showed that platforms improved conditions in terms of awkward postures, static postures and the use of grip related muscles. In another cited work within the meta-analysis, work-related musculoskeletal disorders were studied among 12 Indian farmers by utilizing a body map and a Visual Analogue Discomfort for data gathering. Their results showed that all participants had MSDs in the neck, shoulder, upper arm, and fingers. It also showed that discomfort ratings among females was higher than among male workers.

In Bao's et al. study (2013), although their main focus was on the upper and lower back, participants reported higher ache/pain on their left hand/wrist region when the small basket was used. This behavior was also observed for the right hand/wrist region. Thus, supporting the need for the study of the biomechanical risks on the hands and wrists areas of the coffee collectors. Table 2.1 provides a summary of the research articles in the literature and classifies the findings based on body part studied, type of crop, methodology, and geographical zone. In general, previous research in this field suggest high forces and repetition in the hand as relevant job factors during agricultural activities, but there is a dearth of information related to the evaluation of hand forces in the coffee harvesting process.

2.2 Evaluation Tools

Due to the repetitive nature of the task, different evaluation tools and equipment have been studied. The ones mentioned subsequently have been implemented in studies evaluating risks in different repetitive tasks. Electromyography has been used in different studies (Bao et al., 2013; Jin et al., 2009) to evaluate muscle loading. Moreover, surveys, such as the Rapid Upper Limb Assessment (RULA) and Occupational Repetitive Assessment (OCRA), are common survey tools used to evaluate work-related risks. To evaluate the frequency and duration of a task the American Congress of Governmental Industrial Hygienists (ACGIH) implemented hand activity level (HAL) for jobs ranging from 4 to 8 hours (ACGIH, 2017).

Table 2.1 Summary of research studies in agriculture by body part, crop, methodology and geographical zone.

Body part	Crop	Equipment, Tools and Methods	Geographic Zone
Upper extremity-(hand)	Grapes [a,b]	Musculoeskeletal pain and symptoms survey, NIOSH Lifting Index	California, USA
Upper extremity-(upper arm)	Apples [c]	Triaxial inclinometers, LabVIEW, 2012Borg CR10 scale	Washington, USA
Low back, Upper extremities, Lower extremities, Upper back and Neck	Agriculture [d]	Literature Review	USA
Low back, Upper Extremities, Lower extremities, Upper back and Neck	Agriculture [e]	Literature Review	USA, Asia, Brazil
Low back and Lower extremities	Peppers [f]	Electromyography and lumbar motion monitor	North Carolina, USA
Upper extremities (wrist, hands, shoulder, arms), Low back and Neck	Tea leaf [g]	Polar Heart Rate monitor, Rating of perceived Exertion (RPE), Occupational Repetitive Assessment (OCRA) and Quick Exposure Check (QEC)	Assam, India
Low back and Upper back	Coffee [h]	Electromyography, Muscle aches and pains symptoms survey	Washington, USA

Authors: (a) Duraj, et al. (2000); (b) Biddle (2013); (c) Thamsuwam, et al. (2014); (d) Davis & Kotowski (2007); (e) Naeini, et al. (2014); (f) Jin, McCulloch, & Mirka (2009); (g) Bhattacharyya & Chakrabarti (2012); (h) Bao, et al. (2013)

2.2.1 Surveys and Questionnaires

There are different survey methods for assessing work related discomforts in the body and risks associated with posture and task. The Rapid Upper Limb Assessment (RULA) method assesses the exposure by using diagrams of body postures and scoring tables to evaluate external load factors and other important factors which influence the load, but it varies between individuals (McAtamney & Nigel Corlett, 1993). Another method is the Workplace Ergonomic Risk Assessment (WERA) in which the evaluator observes and evaluates the task using the tool.

Similarly, the Occupational Repetitive Assessment (OCRA) checklist is used to evaluate an initial risk of the presence of repetitive work, while the OCRA Index method provides a more precise analytical risk assessment for designing and redesigning jobs.

Another method is the Quick Exposure Check (QEC) which was designed to assess the changes in exposure to musculoskeletal risk factors of the back, shoulders, arms, hands/wrist, and neck before and after an ergonomic intervention. The QEC helps prevent WRMSD’s by examining static and dynamic tasks that include repetitive actions, pressure, force, position, and duration, to estimate the risk level of body posture by involving movement repetition elements, energy/burden, and work lengths (Bidiawati & Suryani, 2015). Finally, the Nordic Musculoskeletal Questionnaire (NMQ) is used to quantify musculoskeletal pain in 9 body regions, including: neck, shoulders, elbows, hands/wrists, upper back, lower back, hips, knees and feet/ankles. This tool includes an image of the body and several questions referring to the areas of the body (Kuorinka et al. 1987).

2.2.2 Pressure Mapping

Since there is a need to quantify the forces performed during coffee harvesting for this study, the literature review evidenced several studies that have used force sensors to quantify grip forces and evaluate ergonomic risks in the process of enhancing excising product designs. In particular, the Nexgen Glove Pressure Mapping System has been used to evaluate contact pressures on the palm for the task of serving coffee (Proma & Imrhan, 2013). In this task, activities such as lifting and pouring the liquid into a cup were evaluated, focusing on the grasping, lifting and pouring elements of the task. Researchers found that the pressure on the hand was affected by the liquid level, lift level and the phase of lifting. Earlier, Freund, Toivonen and Takala (2002) focused their work on the development of a model of fingertip forces on a cylindrical handle of ten volunteers. The sensors on their experiment were mounted on the different cylindrical handles, and the procedure included performing the grip test at 5 different force levels for five seconds, which was repeated three times. Their results showed that only 10% of variation in the model may be attributed to the grip force, indicating a modeling error. One source of error in their analysis could be attributed to the multiple data sources that were used to setup the parameters in the model.

In a similar study (Aldien, Welcome, Rakheja, Dong, & Boileau, 2005), contact pressure between hand-handle was studied using the EMED measurement system, which is a mat used to collect pressure data by Novel. Three handles were used to measure push and grip force in four different levels. By performing a two-way ANOVA, they showed that the grip force and handle size, and push and grip force had a significant interaction. It was demonstrated that the peak pressure had a linear relationship with the grip and push forces. Results indicated that the magnitudes and distribution of hand-handle interface pressure during gripping and pushing tasks vary with the grip and push force applied, and the handle size. Although our study does not involve a hand tool, this study is relevant in terms of the relationships found using an EMED pressure mapping system and force parameters.

Similar works with pressure sensors have been performed in the area of periodontal activities such as periodontal scaling and root planning (Dong, Barr, Loomer, & Rempel, 2005; Villanueva, Dong, & Rempel, 2007). In 2005, the study was conducted using 12 students with the knowledge on how to perform the task, but with no experience evaluating three different finger rest positions. Electromyography was used to obtain data during the periodontal scaling tasks, using electrodes in the right forearm. To evaluate pinch force, a pressure sensor was situated on the handle of the tool used for scaling. An ANOVA was performed and proved that every factor was significant although the paper did not include the statistical test results to validate their findings.

In 2007, the study was replicated with 12 individuals in the age group of 26 to 50 years old, this time including experienced and inexperienced participants in periodontal activities. A biomechanical model was developed for the pinch force and a linear regression analysis was performed to compare the biomechanical model to the evaluated data. The biomechanical model approximated the pinch force for the experienced dentist reasonably, while it had difficulty predicting for the inexperienced. These findings suggest that in tasks that require manual dexterity, experienced workers should be targeted for evaluation.

Based on the literature review findings, the next chapter describes the objectives for the research work, along with its contributions.

3 OBJECTIVES

Although the risks of MSD's and other aspects have been studied in different types of crop harvesting, there is a dearth of information about MSD risks associated with coffee harvesting. This research aims to:

1) Explore and document the biomechanical risks in the hand and wrist during manual coffee harvesting, through a mixed methods approach.
2) Provide empirical evidence of finger and hand forces for two different harvesting methods (i.e. hand picking and scraping).
3) Provide qualitative data of worker musculoskeletal discomfort and postural analysis.

As the main contribution of this research work, qualitative and quantitative evidence for risk factors in coffee harvesting will be documented, considering two different harvesting methods used in Puerto Rico.

The following chapter will provide details about the methodology used for this research work, focusing on participants, equipment, data collection process and data analysis techniques.

4 METHODOLOGY

4.1 Participants

The study was conducted with randomly selected group of seven voluntary agricultural workers in Puerto Rico, five men and two women. These participants were given a monetary compensation of five dollars for their time, after completing the recording session for each method. Therefore, participants could obtain up to 10 dollars for their participation in the study. Table 4.1 presents the relevant descriptive statistics about the sample. Participant demographics show that they had 3 to 55 years of experience in harvesting coffee. The average age of male participants was 49 years old, while females had an average age of 55 years. All participants worked around 40 hours per week, and with only one exception, they performed other agricultural activities besides coffee harvesting. Four participants work at Adjuntas, two at Yauco, and the last participant works at Coamo, Puerto Rico.

Table 4.1 Descriptive statistics of participants (Average ± SD)

	Male	**Female**
Age (years)	49±15	55.5±14.8
Height (cm)	168.7±9.1	170.8
Weight (kg)	75.9±6.5	70.98±10.6
Hours worked (hrs/week)	35.8±5.20	33.75±5.3

4.2 Equipment

The coffee harvesting activities were video recorded using a Sony Handycam. The videos served as the basis for using Rapid Upper Limb Assessment (RULA) to evaluate the participant's posture and exposure to repetitive tasks during coffee harvesting. Hand pressure data was obtained by using a NexGen Pressure Mapping (GPM) System. This equipment was calibrated beforehand through a series of tests in the laboratory setting, prior to the study. Participants were asked to wear the GPM pressure measuring sensors, attached to a vinyl glove, on the dominant hand to study the force and pressure in the hands and fingers during the harvesting task for selective picking and scraping methods.

4.3 Procedure

4.3.1 Questionnaire

This study was submitted to the UPRM IRB committee for approval prior to commencing the study (see Consent Form in 1). After completing the informed consent document, participants responded to a series of demographic and a Musculoskeletal Discomfort questions as an interview (see Appendix B). The Musculoskeletal Discomfort Form was adjusted for the coffee harvesting tasks based on the Nordic Questionnaire (Kuorinka et al., 1987).

4.3.2 Hand Forces During Harvesting

To collect data of the forces applied during harvesting, the NexGen Pressure Mapping System equipment had to be setup to remote sensing, collecting data in an interval of five frames per second. After the initial equipment setup, a Vinyl glove was placed on the dominant hand of the participant, and 24 sensors were placed on specific locations in the phalanges and the head of the metacarpals (as shown in Figure 4.1). This process took from 5 to 10 minutes per participant. Once the sensors were secured in place, the trigger button was pressed to start recording the forces, and the video recording was started.

Each participant started harvesting using the selective method (“Maduro”) for five minutes measured with a stopwatch. After the initial five minutes, the participant either started harvesting using the scraping method (“Raspado”) for five minutes or, as was the case for two of the participants, the plantation was visited on a later date to collect this data. When the task was complete, after 10 minutes of harvesting activity, the glove was taken off and the sensors were removed with care. The equipment was then connected to the computer to transfer the raw data.

Figure 4.1 Sensor locations on dominant hand.

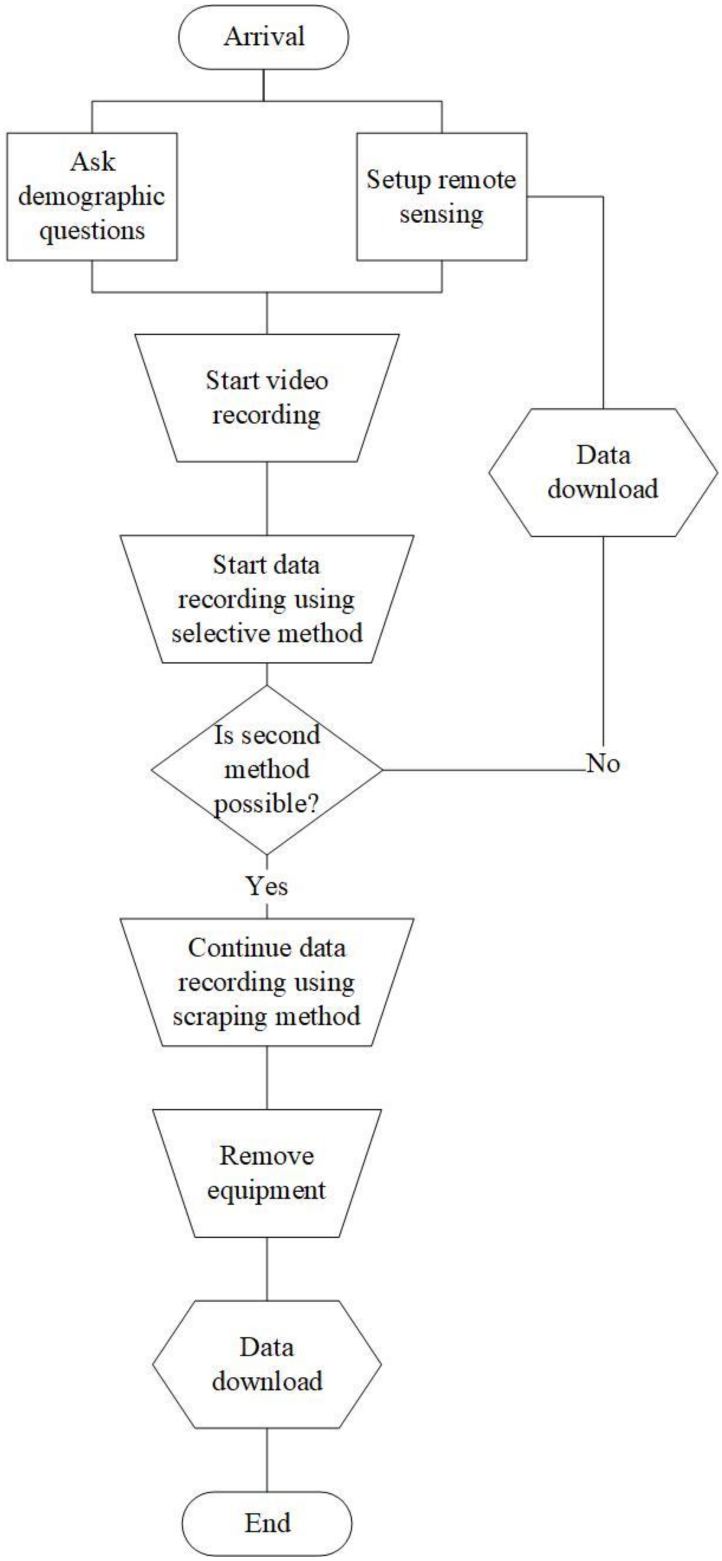


Figure 4.2 Data collection process.

4.4 Data Analysis Techniques

4.4.1 Data Processing

To document the biomechanical impact of the harvesting task, three relevant factors were analyzed from the data, including: hand forces, exertion duration and exertion frequency. The raw data acquired from the GPM system had around 1,500 data points per sensor, for each method per participant. This raw data contained the time frame index, statistics for each time frame, and the data points for the 24 sensors. Data was processed using MATLAB from The Mathworks, Inc. First and foremost, the data for each of 24 sensors, were imported as an array containing each data point for the sensor, for each of the 7 participants. The 48 matrices were divided into several other matrices that include the time frame value in the first column then the force value for each participant in the second column. This was performed for each of the 24 sensors, for each harvesting method. Afterwards, the rows in which the pressure value was 0 was removed from the data set as it represented there was no force exerted.

4.4.2 Statistical Analysis

The first step in the data analysis was to verify if the data followed a normal distribution. For this purpose, a normality test, with a confidence level of 95%, an independence test and a variance homogeneity test were conducted using Minitab. Since the results did not comply with the normality test, raw data for each sensor was transformed. The data was then compared taking into account the participant and harvesting method as factors within the ANOVA. Then, for each sensor, significant factors were analyzed with a pairwise comparison using the Tukey's Method, to establish the relationship between participants and each harvesting method. The Tukey's Method controls the overall error rate of the experiment, at $\alpha=0.05$ in our case, performing a hypothesis test of the differences in means (Montgomery, 2017) for each factor. Also, a Main Effects plot was used to visually analyze the difference of means for each level of the two categorical factors, the participants and the method used.

Once proven that each participant and harvesting method was significantly different, a Pareto analysis was performed to determine which sensors best described the data for each participant and method. To perform the Pareto analysis, the maximum force in a specific time frame or instance was identified and the sensor number was recorded. The number of occurrences for each sensor was recorded and the sensors that contributed to 80% of occurrences with the maximum force were taken as the most active sensors that would best represent how the hand exerts force.

Finally, for each harvesting method, the average, minimum and maximum force, and exertion duration were calculated. The frequency of exertion was calculated considering the total number of exertions observed during recorded task. The frequency of exertion and its duration were compared to the Threshold Limit Value (TLV) on Hand Activity Level (HAL) (ACGIH, 2017). For the selective harvesting method, the force was compared to the maximum acceptable force during pinch force. For the scraping harvesting method, the force was compared to the maximum acceptable force during grip force. The HAL was calculated with the following equation:

$$HAL = 6.56 \, ln \, D \left[\frac{F^{1.31}}{1+3.18 \, F^{1.31}} \right] \tag{4-1}$$

where D is the duty cycle (%) calculated by,

$$D = \frac{Exertion\ time}{exertion\ time + rest\ time} \times 100 \qquad (4\text{-}2)$$

and F is the hand exertion frequency [exertions/s].

HAL results were used along with the Normalized Peak Force to generate a graph to compare research findings to the TLVs. To obtain the Normalized Peak Force the 90th percentile of the maximum forces exerted were taken for each significant sensor and divided by the average maximum forces that can be exerted for each position, as described in the documentation of the TLVs of the ACGIH; griping position for scraping and pulp pinching for selective picking.

Finally, to analyze the relationship between qualitative and quantitative data, the correlation between the different sensors for the two harvesting methods was calculated. Then, a Principal Component Analysis (PCA) was used to simplify the model from a 24 dimension to a smaller dimension analysis. To perform the PCA, a scree plot for each method including the 24 sensors was performed to determine the number of principal components needed. The resulting principal component eigen vectors were obtained from the PCA and the values were multiplied with the matrices of the data to obtain corresponding prediction vectors. A regression analysis was performed with the prediction vectors incorporating the different factors. The factors of interest included in the model were: age, gender, height, weight, experience, shift duration and hand pressure based on harvesting method (hand picking or scraping).

Finally, data obtained from the Rapid Upper Limb Assessment as well as the Musculoskeletal Discomfort Questionnaire were analyzed using descriptive statistics.

4.4.4 Postural Analysis

A postural assessment of the task was performed using Rapid Upper Limb Assessment (RULA) (raw data in Appendix D), using NexGen Ergonomics: ErgoIntelligence UEA software. RULA is a one-page ergonomic assessment that considers biomechanical and postural load of the task in the neck, trunk and upper extremities of an individual worker considering body posture, force and repetition (Middlesworth, n.d.). To conduct a postural analysis, videos of each participants were captured while they were harvesting coffee. The video was observed, and the most common sustained posture was analyzed. Posture varied due to harvesting method (selective or picking), tree height and if the worker had harvesting bag. Based on the research data tree height was classified as low trees (measuring less than 4 feet), medium size trees (4 feet to 6 feet tall) and high trees (taller than 6 feet). The use of a harvesting bag was considered as a variable in the analysis as it would increase the force exerted by the body while carrying it.

4.4.5 Questionnaire

Each worker answered a series of demographic questions as an interview, which included: gender, age, weight, time working in this industry and if they performed other agricultural work. These responses along with answers to the Musculoskeletal Discomfort Form were subjected to a descriptive statistics analysis to better comprehend the worker's demographics. Appendix C includes the summary of raw data for each question.

5 RESULTS AND DISCUSSION

5.1 Hand Forces

The pressure mapping glove was used during the harvesting task to record the pressure exerted by 24 different locations throughout the hand. Figure 5.1 represents the location of each sensor placed on the phalanges and head of the metacarpals. Four sensors were placed in the phalange of the thumb (phalange 1), four of the index (phalange 2), middle (phalange 3), and ring finger (phalange 4). For each of the three central fingers, another sensor was placed in the head of the metacarpals. On the little finger (phalange 5), 3 sensors were located on the phalange and 2 on the metacarpal. The average, maximum and minimum forces for each of the sensors are in Appendix F.

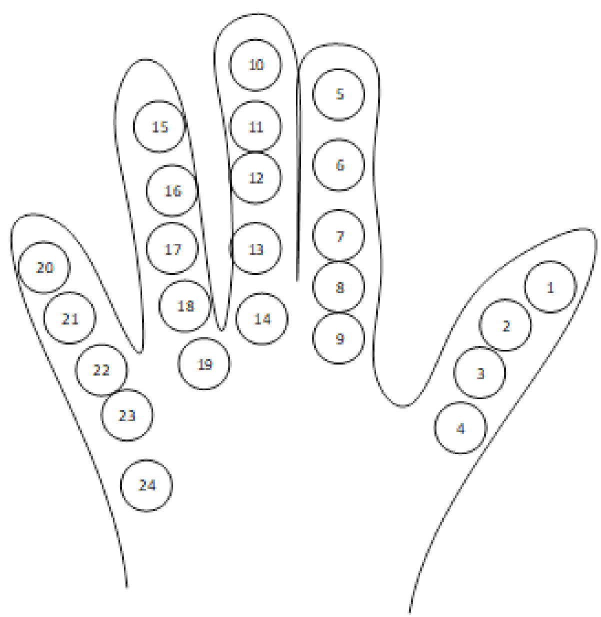


Figure 5.1 Position of the 24 sensors on the hand.

The results of the ANOVA analysis (α=0.05, p-value=0.000) concluded that there is a significant difference between the forces applied by participant, as a significant factor, for each sensor. A multiple comparison between participants was performed using Tukey's Method. For the first sensor it is observed that the group of 7 participants is divided into 5 groups for the Tukey pairwise comparison. Results for Sensor 1 are shown in Table 5.1 to Table 5.3 and Figures 5.3 and 5.4. The outputs of the statistical analysis for the other 23 sensors are presented in Appendix E in Tables E.1-E.48. The Main Effects for sensor 1, shown in Figure 5.2 presents a comparison for mean force (transformed) based on participants and harvesting method. Results show that the harvesting method influences the means of each of the sensors. For sensors 2, 5, 8, 12, 14, 17-20 and 24, the means of the selective method is lower than the scraping method. This is sufficient evidence to evaluate each worker individually.

The Pareto analysis of the forces exerted by each participant, highlights the different sensors that were involved in executing 80% or more of the of the pressure for that participant, per method. Table 5.4 shows the sensors that resulted from the Pareto Analysis. For each participant, at least one sensor is representative as active in both methods.

Table 5.1 Analysis of Variance for Sensor 1.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	90.03	15.0056	1384.38	0
Method	1	25.28	25.2757	2331.86	0
Error	9125	98.91	0.0108		
Lack-of-Fit	5	28.41	5.6812	734.9	0
Pure Error	9120	70.5	0.0077		
Total	9132	235.33			

Table 5.2 Model Summary for ANOVA for Sensor 1.

S	R-sq	R-sq(adj)	R-sq(pred)
0.104112	57.97%	57.94%	57.89%

Table 5.3 Tukey Pairwise Comparison grouping for Sensor 1.

Participant	N	Mean	Grouping				
6	211	-1.0051	A				
5	564	-1.0213		B			
1	206	-1.025		B	C		
3	1109	-1.0261		B	C		
7	254	-1.037			C		
4	935	-1.0574				D	
2	758	-1.093					E

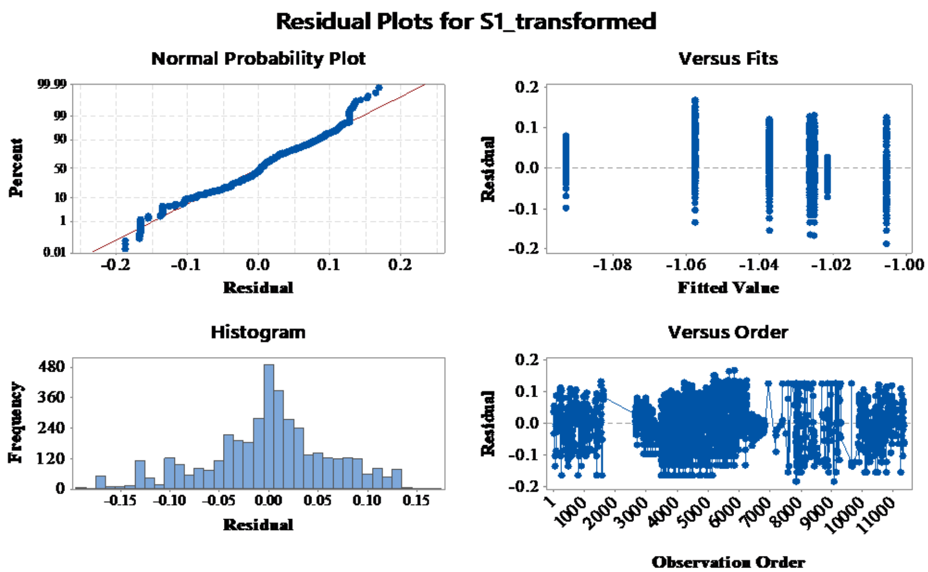


Figure 5.3 Residual Plot for Sensor 1 after transformation.

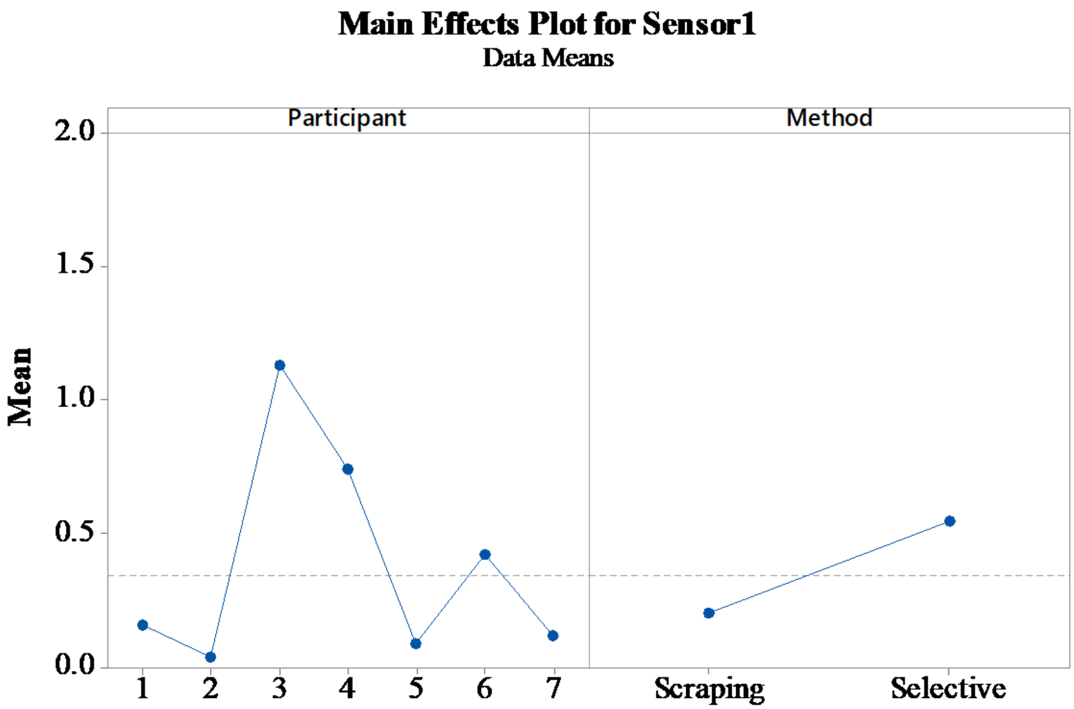


Figure 5.4 Main Effect Plot for sensor 1 for participant and method variable.

Average force values exerted by participant is shown with Box and Whiskers plots shown in Figures 5.4 - 5.10 demonstrate that forces exerted vary for each participant. On Figure 5.12, the Normalized Peak Forces (NPF) is evaluated considering the Activity Level (AL) and Threshold Limit Values (TLV) for hand movements established by the ACGIH. The NPF obtained for our data are within the range of 8.72 x10^{-5} N to 3.99 N. HAL ratings can be rated using the following information: for a HAL of 0 hands are idle most of the time with no regular exertions, a HAL of 2 is there are very slow motions with consistent conspicuous long pauses. A HAL of 4 indicates slow steady exertions with frequent brief pauses. Steady exertions with infrequent pauses gives a HAL of 6, while rapid steady motion with no regular pauses gives a HAL of 8. Lastly, continuous exertions indicate a HAL of 10, which should not be reached.

For participant 1, sensors 5 and 23 are above the AL values at a HAL of 7, for selective picking while only sensor 16 is above the AL value for a HAL of 7 for scraping. The HAL value calculated for the sensors for participant 1 gave 8, the sensors 7 and 11 for the selective method, and the sensors 2, 6, 7, 8, and 12 for scraping were between the AL and TLV. For participant 2, sensor 5 and sensor 20 are between the AL and TLV for a HAL of 8 and 7, respectively. Participant 3 gave an NPF between the AL and TLV for sensors 1, 5, 7 and 23 for selective picking and sensors 1, 7, 10, and 21 for scraping method. For selective picking, sensor 2's NPF is above TVL while sensor 8 and 16 are between AL and TLV for participant 4. Meanwhile, for scraping method for the same participant the only sensor between the AL and TLV was sensor 11. All HAL values for the sensors that were indicated to be significant by the Pareto analysis are represented in Table 5.5 The rest of the values and the values above mentioned are indicated in Table 5.4 by a star for values between the AL and TLV and by two stars for values above the TLV. The solid line in Figure 5.12 indicates the combination of NPF and HAL related with an increased occurrence of musculoskeletal disorders, while the dashed line corresponds to the AL which recommends to review the activities associated with the task. Even though there were no similar patterns amongst participants for the sensors that were activated during the activity, findings show that during the activity at least 2 sensors showed activity levels above the action limit suggesting review of the activity for each method.

Table 5.4 Pareto analysis results for most active sensors per participant (S= selective method, R=scraping method and *=sensors with HAL and NPF between AL and TLV, and **=HAL and NPF above TLV).

		Participant						
Phalanges	**Sensor**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	1			S*, R*				
	2	R*		S, R	S*, R			S*, R*
	3					S, R	S	
	4				S	R*		
2	5	S*	S*	S*	R	R		R*
	6	S*, R*		S, R		R	S	S**, R*
	7	S*, R*		S*, R*	S, R	S		S*, R*
	8	R*	R		S*, R	S	S, R	
	9			R			S, R	
3	10	R		S, R*	S, R			
	11	S*, R			R*	R	S	
	12	S, R*	S		S, R			
	13							
	14							
4	15				R			
	16	R*			S*		S*	
	17		S, R			R*	R	
	18			R				
	19							
5	20		S*					
	21			R*				S
	22	S, R						
	23	S*		S*		R	S*	
	24							

Table 5.5 Hand Activity Level for sensors indicated in pareto analysis (S= selective method, R=scraping method).

Hand Activity Level

		Hand is idle, no regular exertions		Very slow motions or long pauses		Slow steady motions		Steady motions; infrequent pause		Rapid steady motions; no regular pauses		Difficulty keeping up
Phalanges	**Sensor**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	1								R3	S3		
1	**2**		S4, R4		S3, R3			S7		R1, R7		
	3		S5, S6				R5					
	4					S4			R5			
	5							R4, R5	S1	S2, R7		
	6		S6	R3			S3	R5	S1, R7	R1, S7		
2	**7**		S5					R4	S3, R3	S1, R1, S4, S7, R7		
	8		R2, R4, S5, S6, R6						S4	R1		
	9		S6, R6					R3				
	10		R4		S3	S4	R1		R3			
	11		S6				R1	R5	R4	S1		
3	**12**			R4	S2				S4	R1	S1	
	13											
	14											
	15											
	16		S2					S4, R4	R1, S6			
4	**17**		R2, R6						R5			
	18							R3				
	19											
	20								S2			
	21							S7	R3			
	22						S1				R1	
5	**23**				R5				S1, S3, S6			
	24											

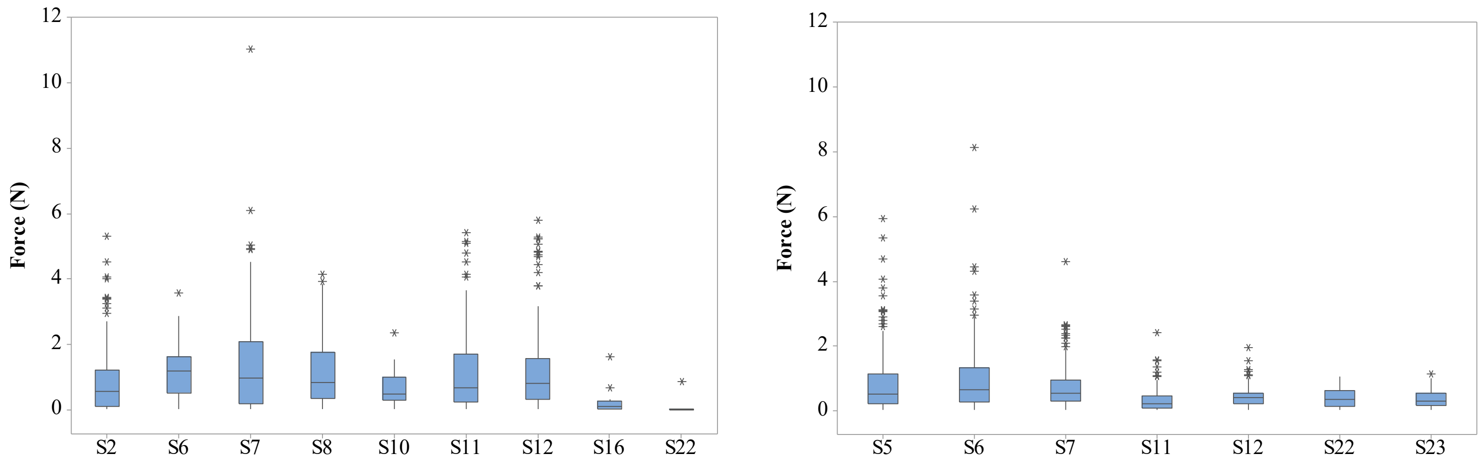
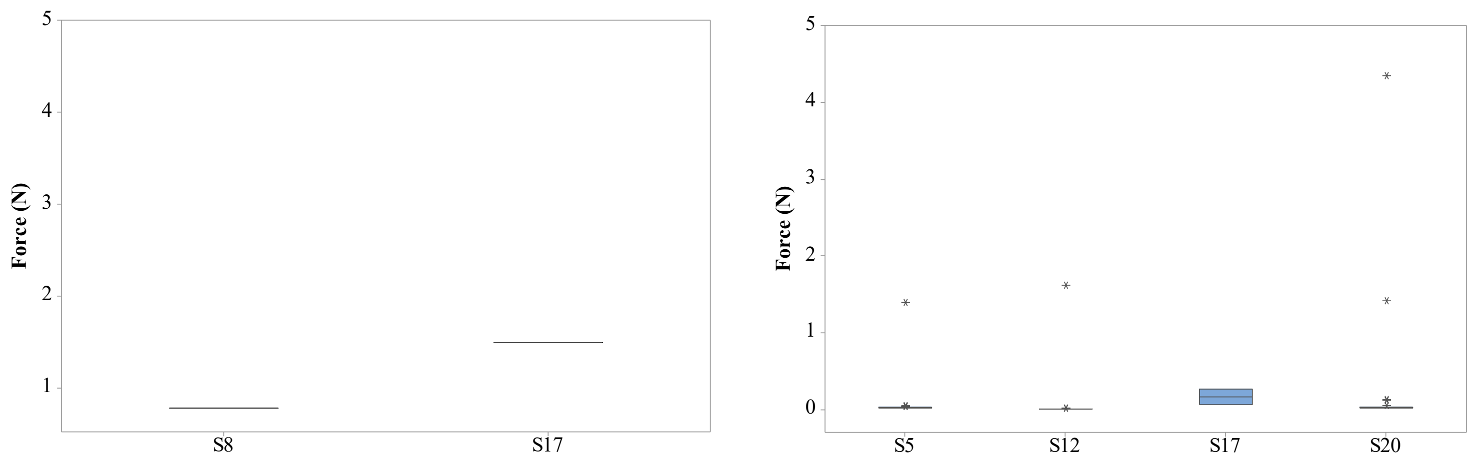


Figure 5.5 Boxplot of forces applied to sensors by participant 1 during scraping method (left) and selective picking (right)



t

Figure 5.6 Boxplot of forces applied to sensors by participant 2 during scraping method (left) and selective picking (right)

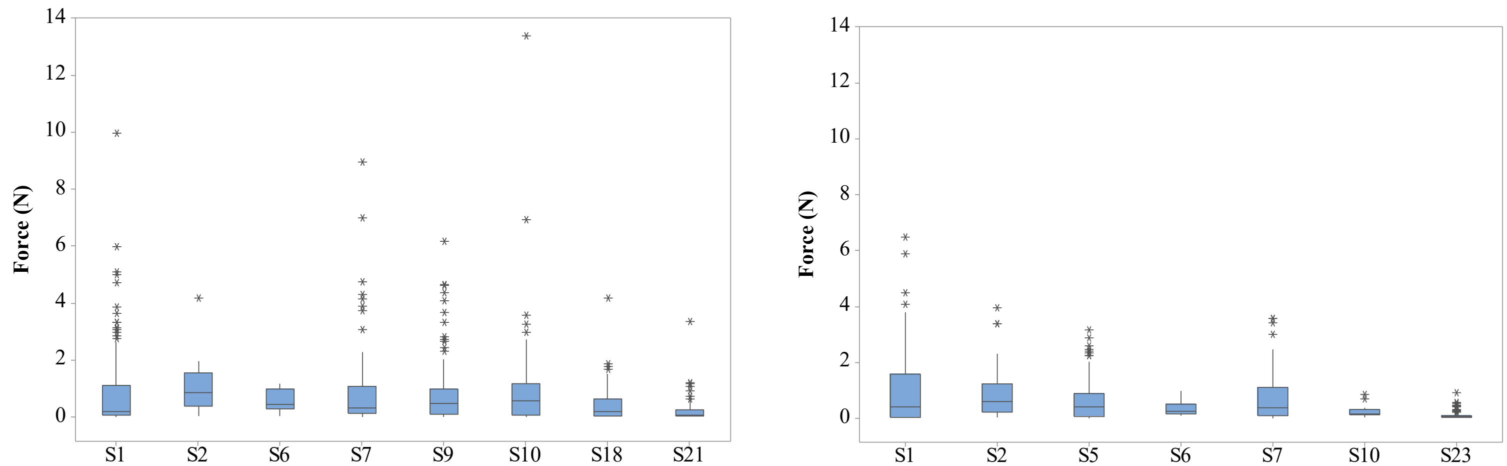


Figure 5.7 Boxplot of forces applied to sensors by participant 3 during scraping method (left) and selective picking (right).

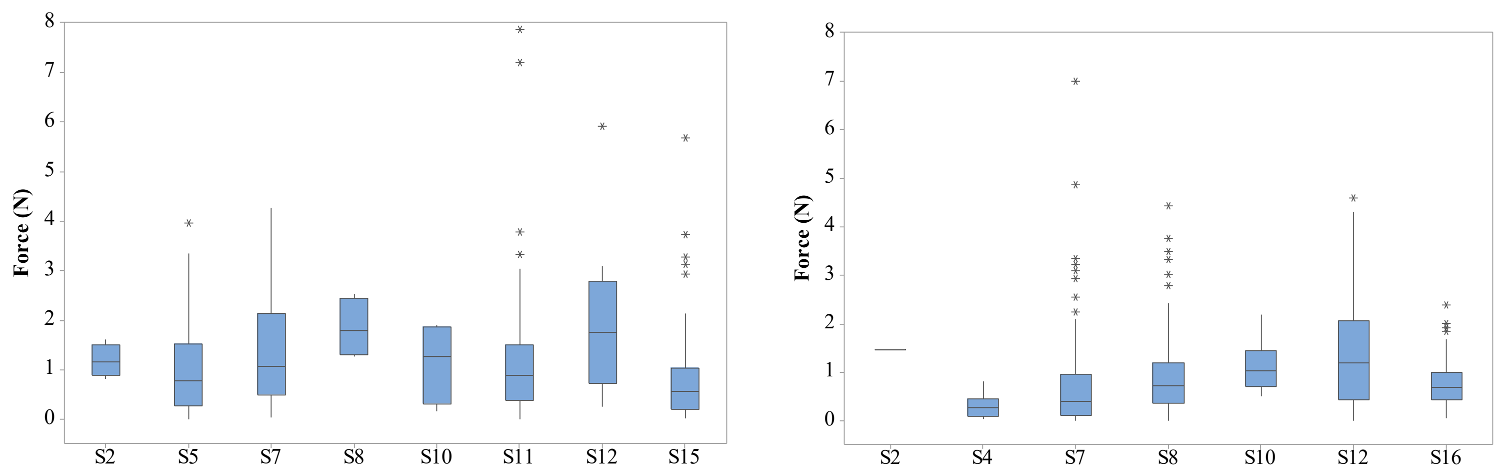


Figure 5.8 Boxplot of forces applied to sensors by participant 4 for scraping method (left) and selective picking (right).

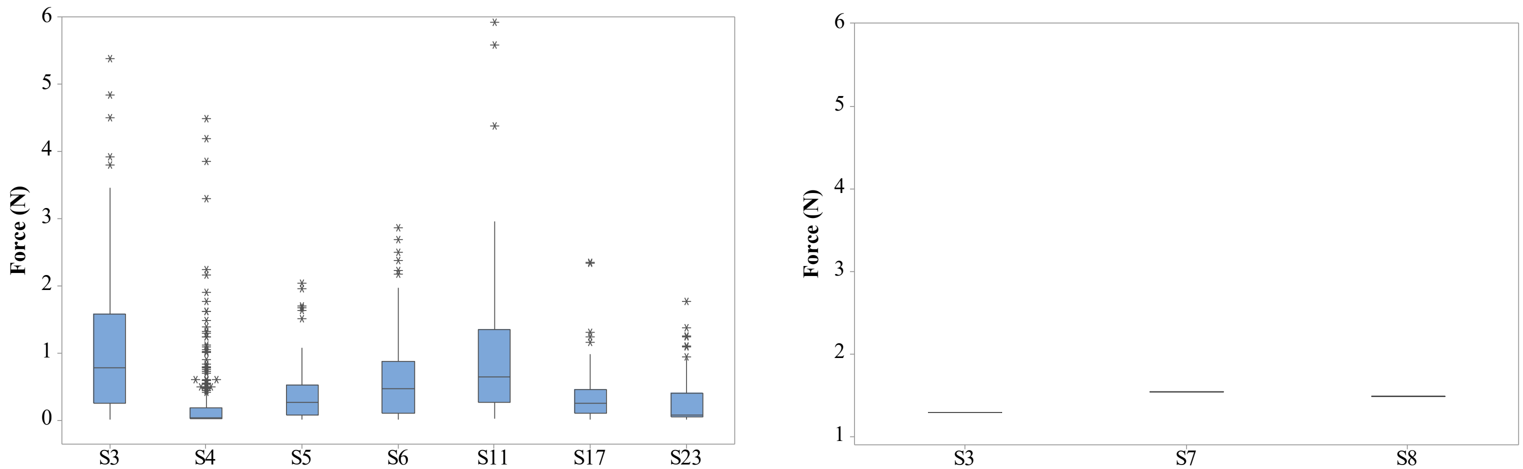


Figure 5.9 Boxplot of forces applied to sensors by participant 5 during scraping method (left) and selective picking (right).

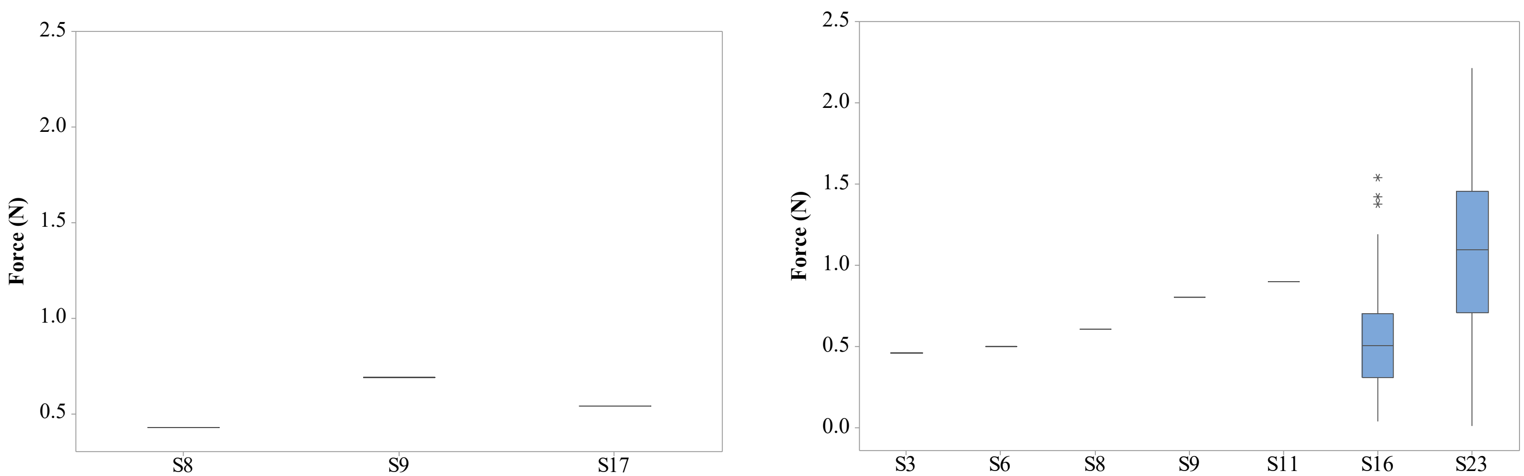


Figure 5.10 Boxplot of force applied to sensors by participant 6 during scraping method (left) and selective picking (right).

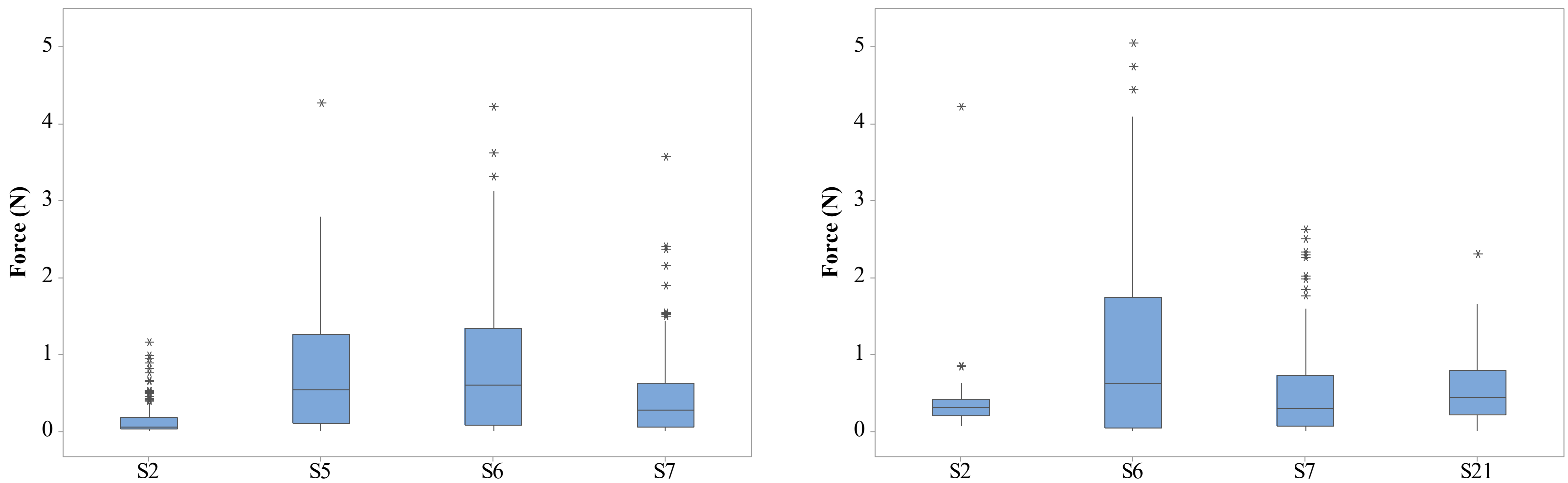


Figure 5.11 Boxplot of force applied to sensors by participant 7 during scraping method (left) and selective picking (right).

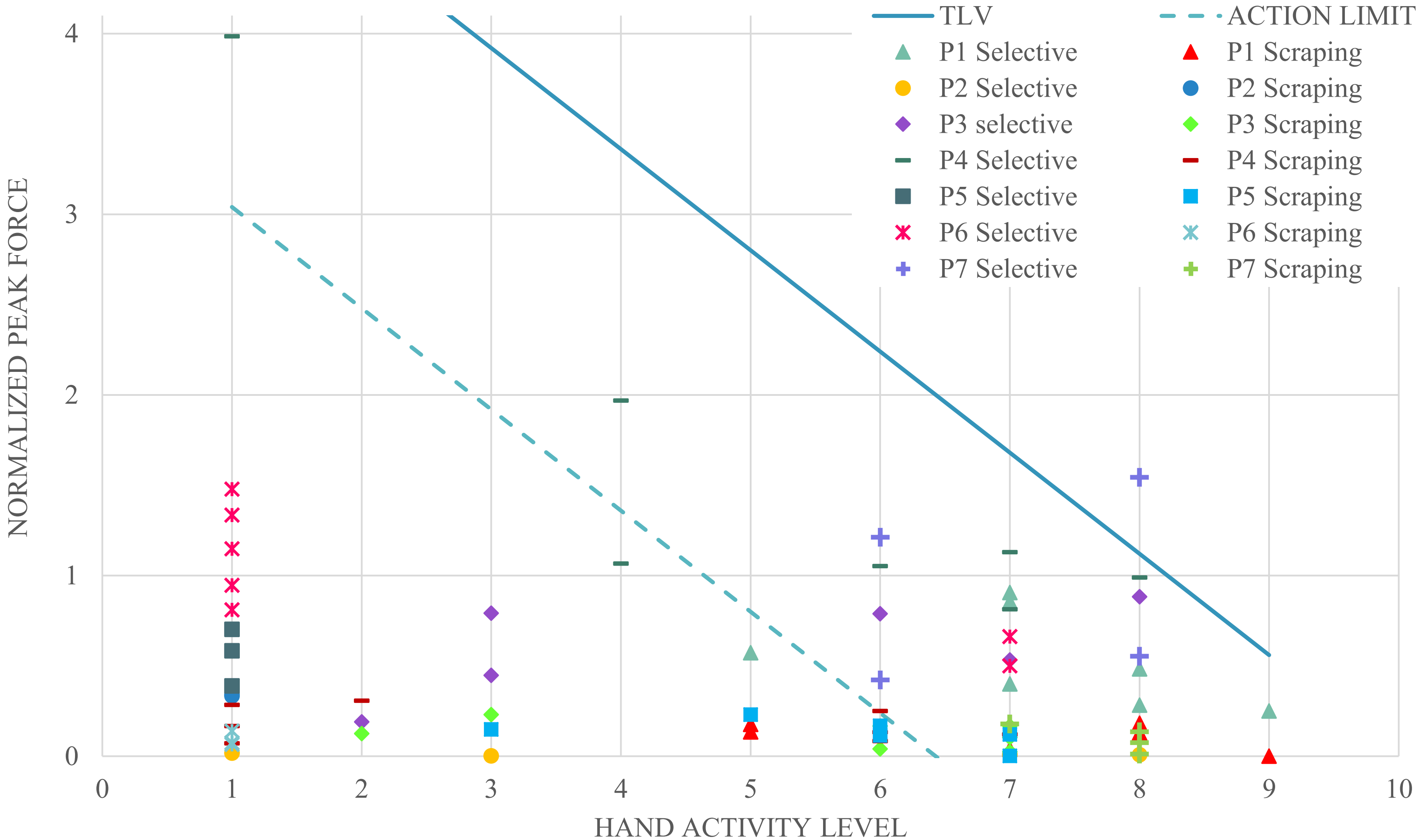


Figure 5.12 Normalized Peak force versus Hand Activity Level for each participant and method.

5.1.1 Principal components Analysis

A principal component analysis was performed to reduce the complexity of the desired model and observe the relationship between the pressure exerted in the sensors and the qualitative data obtained from the questionnaire. A correlation matrix was generated to verify that the sensors do not have high multicollinearity. Figure 5.13 and Figure 5.14 show the correlations between the sensors for the selective and scraping method, respectively. The correlation matrix indicated a moderate correlation between the specified sensors (R between 0.47 and 0.93). Seven principal component vectors were selected according with the scree plot in Figure 5.15 and Figure 5.16. When assessing the scree plot, a steep curve which bends at factor 4 and flattens at factor 7 is observed. This point is important as it suggests selecting 7 factors for each method. Table 5.6 and Table 5.7 demonstrate the principal component vectors.

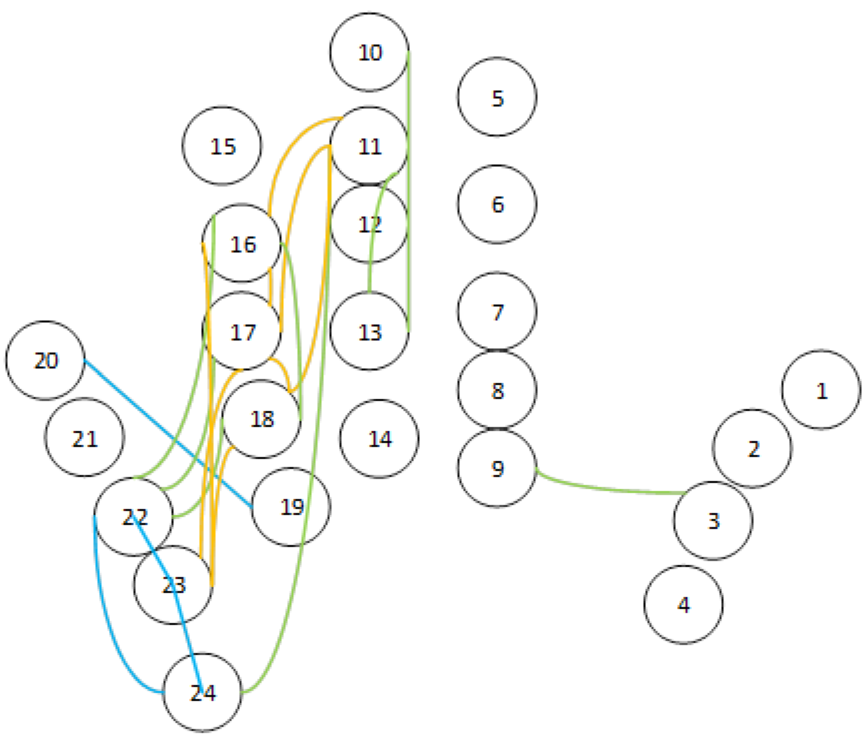


Figure 5.13 Correlation between sensors for selective method.

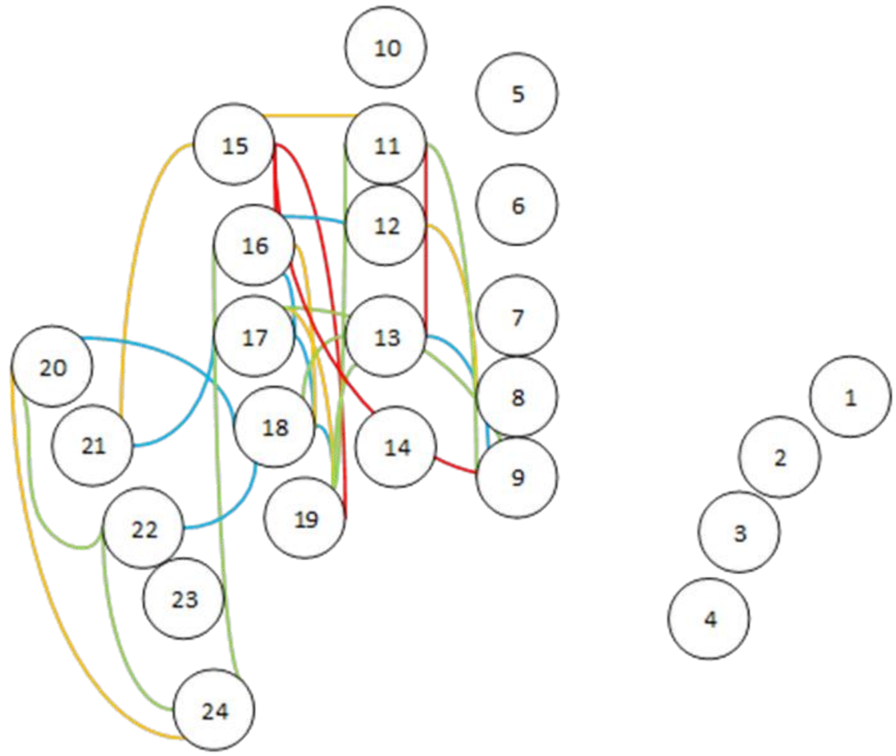


Figure 5.14 Correlation between sensors for scrapping method.

As specified in a previous section, these principal component vectors were multiplied by the data points for each method to obtain the prediction vectors. The factors that were considered important were years of experience, weight, and age for both methods. After performing the regression analysis, the coefficient of determination in the regressions resulted in small values, indicating that the regression is not strong enough to support the regression model predictions. To tackle this, factors were added, and the level of confidence was raised to 99%, but it did not affect the coefficient of determination. This could be because the range of the factors is not large enough to allow detection for the relationship with the sensors.

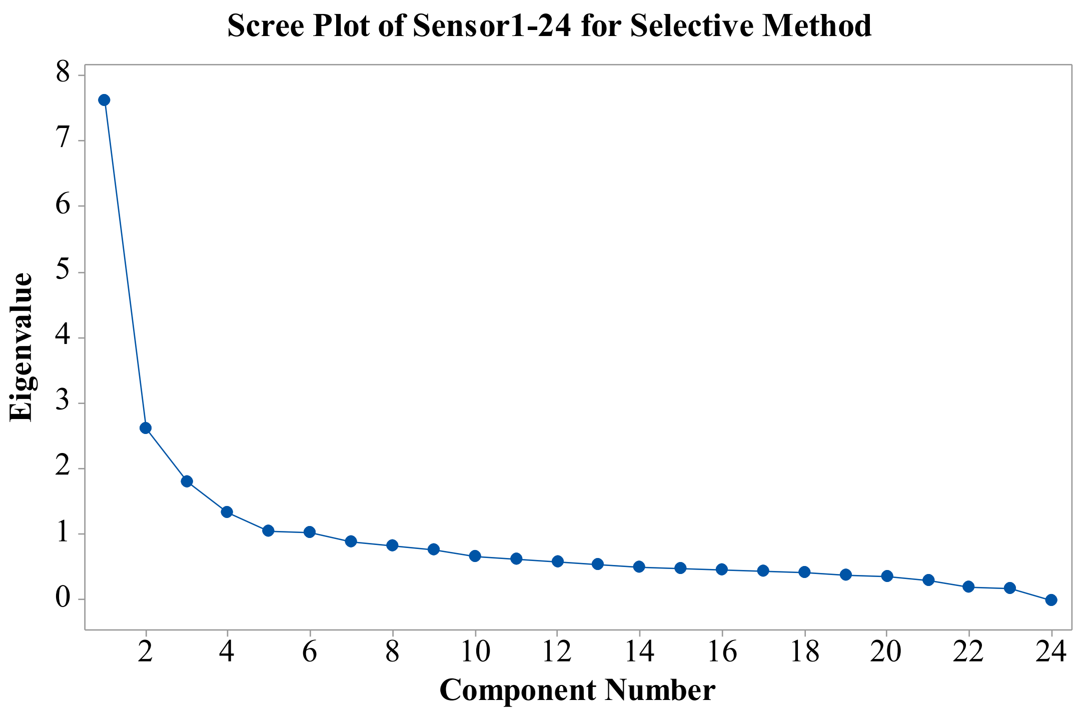


Figure 5.15 Scree Plot of Sensors 1-24 for Selective Method

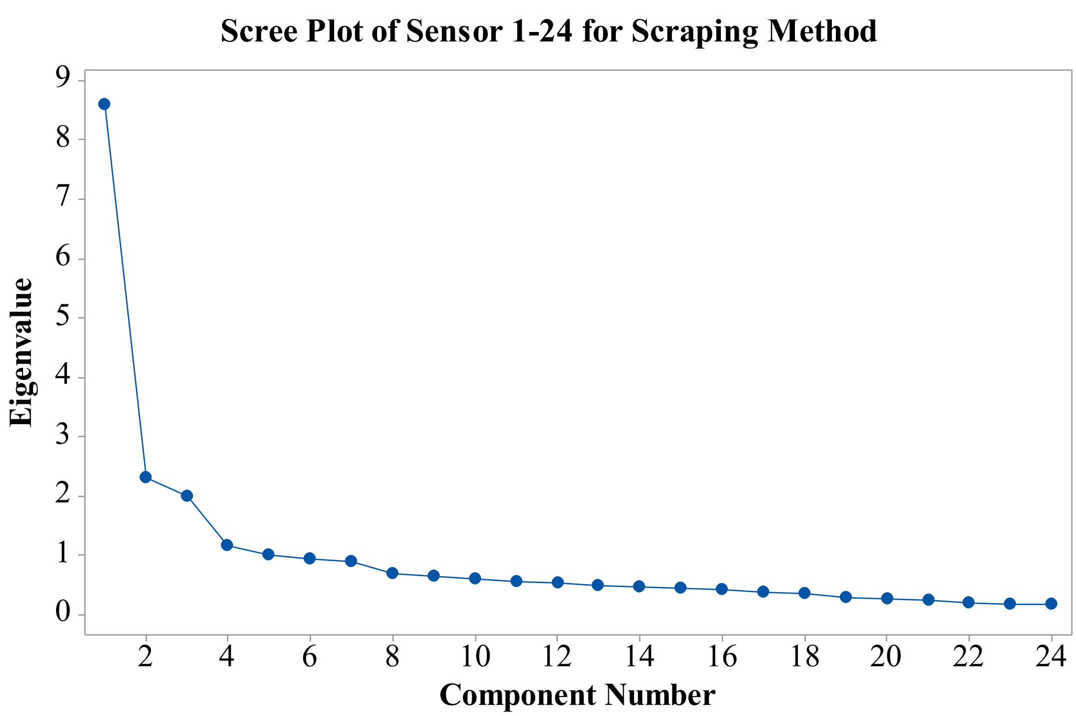


Figure 5.16 Scree Plot for sensors 1-24 for Scrapping Method.

Table 5.6 Principal component vectors for selective method.

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Sensor1	0.054	-0.069	-0.042	0.427	0.167	-0.659	-0.255
Sensor2	0.100	-0.185	-0.420	0.209	-0.333	0.052	0.086
Sensor3	0.171	-0.250	0.313	-0.225	0.037	-0.128	-0.057
Sensor4	0.154	0.004	-0.182	-0.204	-0.306	-0.189	-0.459
Sensor5	0.129	-0.240	0.098	0.274	0.239	-0.180	-0.150
Sensor6	0.094	-0.227	-0.048	0.459	0.125	0.326	0.063
Sensor7	0.138	-0.207	-0.117	0.247	0.076	-0.093	0.527
Sensor8	0.185	-0.274	0.117	-0.138	-0.233	-0.068	0.253
Sensor9	0.189	-0.209	0.326	-0.098	0.102	-0.100	0.101
Sensor10	0.214	-0.088	-0.302	-0.032	-0.244	-0.161	-0.091
Sensor11	0.287	0.024	-0.007	-0.062	-0.027	-0.109	0.026
Sensor12	0.258	-0.304	-0.010	-0.061	-0.055	0.254	-0.121
Sensor13	0.258	-0.304	-0.010	-0.061	-0.055	0.254	-0.121
Sensor14	0.218	-0.047	0.270	-0.162	0.105	-0.013	0.014
Sensor15	0.197	-0.032	-0.376	-0.149	0.173	-0.023	0.062
Sensor16	0.287	0.175	0.030	0.013	-0.098	0.077	-0.110
Sensor17	0.285	0.153	0.165	0.017	0.052	-0.079	-0.038
Sensor18	0.256	0.261	0.114	0.117	-0.009	0.039	0.084
Sensor19	0.185	0.167	-0.237	-0.225	0.405	-0.086	0.221
Sensor20	0.192	0.164	-0.260	-0.210	0.271	-0.068	0.146
Sensor21	0.137	0.044	-0.074	0.127	0.425	0.373	-0.438
Sensor22	0.213	0.329	0.067	0.269	-0.186	0.128	0.062
Sensor23	0.214	0.308	0.244	0.220	-0.213	0.003	0.082
Sensor24	0.248	0.225	-0.072	-0.001	-0.070	0.004	0.002

Table 5.7 Principal component vectors for scraping method

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Sensor1	0.125	-0.080	-0.261	0.355	-0.450	-0.034	-0.229
Sensor2	0.138	-0.389	-0.041	0.167	-0.079	-0.007	-0.122
Sensor3	0.163	0.008	-0.155	-0.421	0.234	0.310	-0.207
Sensor4	0.149	-0.158	0.100	-0.213	-0.317	0.538	0.116
Sensor5	0.152	-0.210	-0.233	0.089	0.235	-0.235	0.463
Sensor6	0.135	-0.370	-0.069	-0.073	0.225	-0.198	0.398
Sensor7	0.202	-0.192	-0.179	0.042	0.243	0.067	-0.182
Sensor8	0.160	-0.334	0.013	-0.146	0.303	0.061	-0.381
Sensor9	0.208	0.081	-0.368	-0.143	-0.049	-0.063	-0.207
Sensor10	0.170	-0.248	0.040	0.220	-0.367	0.070	0.054
Sensor11	0.267	0.076	-0.209	0.087	-0.032	0.016	0.023
Sensor12	0.227	-0.297	0.054	-0.065	-0.052	-0.106	-0.044
Sensor13	0.255	0.007	-0.08	-0.113	-0.193	-0.010	-0.018
Sensor14	0.136	-0.025	0.092	-0.572	-0.374	-0.354	0.126
Sensor15	0.194	0.266	-0.334	0.111	0.072	0.080	0.020
Sensor16	0.260	0.029	0.295	0.139	0.060	-0.085	-0.077
Sensor17	0.236	0.300	-0.088	-0.093	0.059	-0.248	-0.131
Sensor18	0.251	0.113	0.294	-0.133	-0.073	-0.164	0.041
Sensor19	0.232	0.257	-0.032	-0.069	-0.040	0.024	0.093
Sensor20	0.233	0.145	0.333	0.110	0.144	-0.008	-0.121
Sensor21	0.214	0.194	-0.077	0.214	0.009	-0.195	0.044
Sensor22	0.259	0.03	0.306	0.142	0.071	0.135	0.103
Sensor23	0.186	0.158	-0.10	0.022	0.047	0.452	0.442
Sensor24	0.227	0.016	0.304	0.158	0.119	0.044	-0.065

The following is an example of the results obtained from the regression analysis for the prediction vector 1 of the selective method and the scraping method. Additional regression models and results are presented in Appendix D.

Table 5.8 Resulting Analysis of Variance for Selective Method (Vector 1).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	5890.4	1963.46	419.22	0
Experience	1	1181.2	1181.17	252.19	0
Weight	1	1313.9	1313.91	280.54	0
Age	1	1336.2	1336.24	285.31	0
Error	8346	39088.9	4.68		
Lack-of-Fit	2	758.1	379.06	82.52	0
Pure Error	8344	38330.8	4.59		
Total	8349	44979.3			

Table 5.9 Model Summary for Selective Method (Vector 1).

S	R-sq	R-sq(adj)	R-sq(pred)
2.16415	13.10%	13.06%	13.00%

Table 5.10 Coefficients for Selective Method (Vector 1).

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	4.821	0.57	8.46	0	
Experience	-0.07298	0.0046	-15.88	0	10.86
Weight	-0.08578	0.00512	-16.75	0	1.77
Age	0.12867	0.00762	16.89	0	12.58

Regression equation of principal component vector 1 for Selective Method:

$$T_{PRED_{SELECTIVE_{PC1}}} = 4.821 - 0.07298\,Experience - 0.08578\,Weight + 0.12867\,Age \quad (5\text{-}1)$$

Table 5.11 Resulting Analysis of Variance for Scraping Method (Vector 1).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	20089	6696.4	481.48	0
Age	1	16232	16232.2	1167.12	0
Weight	1	5795	5794.7	416.65	0
Experience	1	8477	8476.9	609.5	0
Error	14092	195990	13.9		
Lack-of-Fit	2	13132	6566.2	505.96	0
Pure Error	14090	182858	13		
Total	14095	216080			

Table 5.12 Model Summary for Scraping Method (Vector 1).

S	R-sq	R-sq(adj)	R-sq(pred)
3.72933	9.30%	9.28%	9.23%

Table 5.13 Coefficients for Scraping Method (Vector 1).

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-22.231	0.825	-26.94	0	
Age	0.3859	0.0113	34.16	0	17.3
Weight	0.14836	0.00727	20.41	0	2.99
Experience	-0.17326	0.00702	-24.69	0	14.84

Regression equation of principal component vector 1 for Scraping Method:

$$T_{pred_{scraping_{PC1}}} = -22.231 + 0.3859\,Age + 0.14836\,Weight - 0.17326\,Experience \quad (5\text{-}2)$$

5.2 Postural Analysis

Results show that the final RULA score varied based on the height of the tree, harvesting method, and use of a harvesting bag. Individual RULA evaluations with corresponding images are described in Appendix D. Figure 5.17 presents the average RULA scoring between participants under the same condition, comparing the selective picking method and the scraping method, while also comparing the use of a harvesting bag hung from the worker's neck, and coffee tree height. The figure also depicts three zones in accordance to postural risk based on the RULA scores.

RULA scores between 1 and 3 means acceptable posture, 3 to 4 suggest further investigation and possible change needed, 5 to 6 suggest further investigation/change soon, and 7 requires investigation and implement change (Middlesworth, n.d.). As shown in Figure 5.17, when the participants harvest coffee using the selective method, the height of the tree does not seem to affect the scoring for the task. Average RULA scores for the selective picking method suggests that a change or further investigation is needed. Within the selective picking activity, when posture is analyzed for workers with the harvesting basket, the RULA score recommends to investigate and change the task soon or immediately. This is due to the high weight sustained throughout the harvesting task by placing the basket's straps on the worker's neck.

The postures evaluated while harvesting using the scraping method, showed different scores based on the height of the tree, independent of the use of harvesting bag. For trees taller than 6 feet (high trees) and trees smaller than 4 feet (low trees), RULA scores suggest that further investigation was needed, and the activity should be changed soon. In particular, for trees with height over 6 feet the worker had to reach upward, while for low trees the worker had to bend their trunk forward.

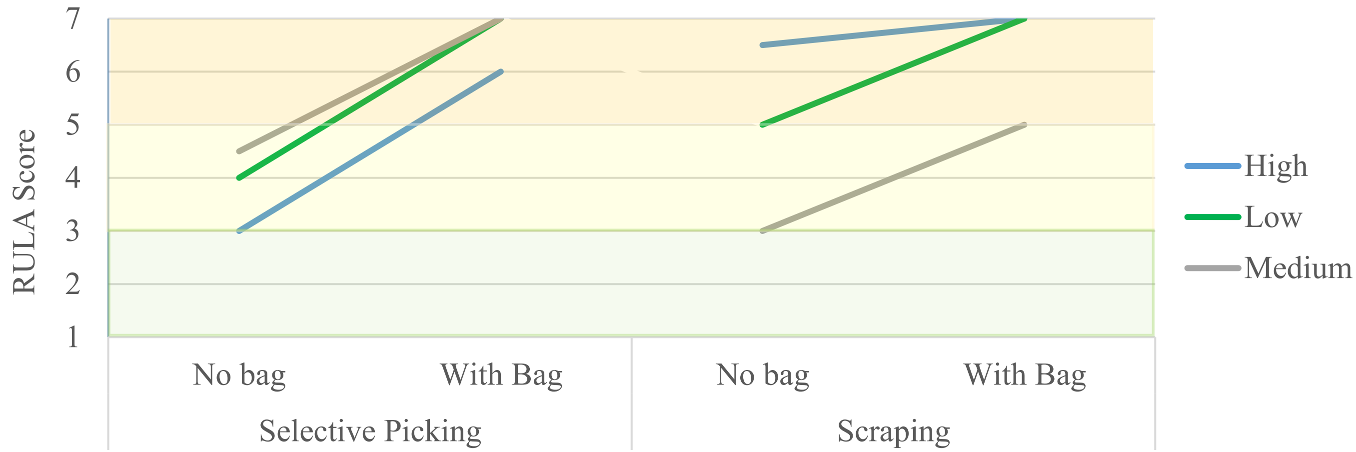


Figure 5.17 Average RULA scores considering harvesting method, use of harvesting bag and tree height

An Analysis of Variance (ANOVA) of the data, was performed for the RULA score as the response variable, with the height of the tree (low, medium and high), use of basket (yes, no) and harvesting method (selective picking, scraping) as the model variables. Based on all data collected for the 7 workers, differences in tree height, use of bag and harvesting method, 20 different RULA analysis were completed. With a confidence level of 90%, significant factors (shown in Table 5.14) were the use of harvesting bag as a main effect, and the interactions between harvesting method with tree and the use of the harvesting bag.

These results suggest that the use of a harvesting bag is a critical factor posing an ergonomic risk that needs further investigation and consideration for redesigning the task, methods and tools.

Table 5.14 ANOVA results for study variables based on RULA scores

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Method	1	0.4653	0.4653	1.31	0.277
Bag	1	22.219	22.219	62.51	0.000*
Tree	2	2.2403	1.1201	3.15	0.083
Method*Bag	1	2.7867	2.7867	7.84	0.017*
Method*Tree	2	12.2465	6.1233	17.23	0.000*
Bag*Tree	2	0.5653	0.2826	0.8	0.476
Error	11	3.9097	0.3554		
Lack-of-Fit	2	0.9097	0.4549	1.36	0.304
Pure Error	9	3	0.3333		
Total	20	47.2381			

5.3 Musculoskeletal Discomfort Form

The participants completed a Musculoskeletal Discomfort Form (Appendix B) in which they specified their history of discomfort experience and demographic questions, such as whether they perform other activities related to agriculture, age and years of experience. Demographic characteristics of the sample were described in Chapter 4 (See Table 4.1). When asked whether the participant performed other activities, 85.7% indicated they performed other activities related to agriculture. These activities include: weeding, fertilization, planting, mowing, and plowing. Also, most participants (85.7%) reported that harvesting coffee was less difficult than other agriculture activities. Individual answers to each question are shown in Appendix C.

Participant responses related to pain/discomfort/injury in the past 12 months and in the last 7 days, are shown in Figure 5.18. Results show the lower back, upper back, shoulders and neck were common body areas with most pain/discomfort/ injury. This data is consistent with literature findings (Bao et al., 2013; Bhattacharyya & Chakrabarti, 2012; Naeini et al., 2014). Figure 5.19

shows the percentage of participants who felt that the pain/discomfort/injury prevented normal work performance. For those participants who answered they experienced neck discomfort, 75% indicated that the neck discomfort interfered with their work performance. Only one participant experienced neck discomfort in the 7 days prior to answering the discomfort form. When asked whether they experienced shoulder discomfort, 28.57% indicated they experienced discomfort on their left shoulder, 28.57% experienced discomfort form on the right shoulder, while the rest did not experience discomfort. Findings also show that none of the participants reported discomfort at the elbows. Finally, eighty six percent of the participants reported they experienced hand/wrist discomfort, of which 67% reported it prevented them from performing their tasks.

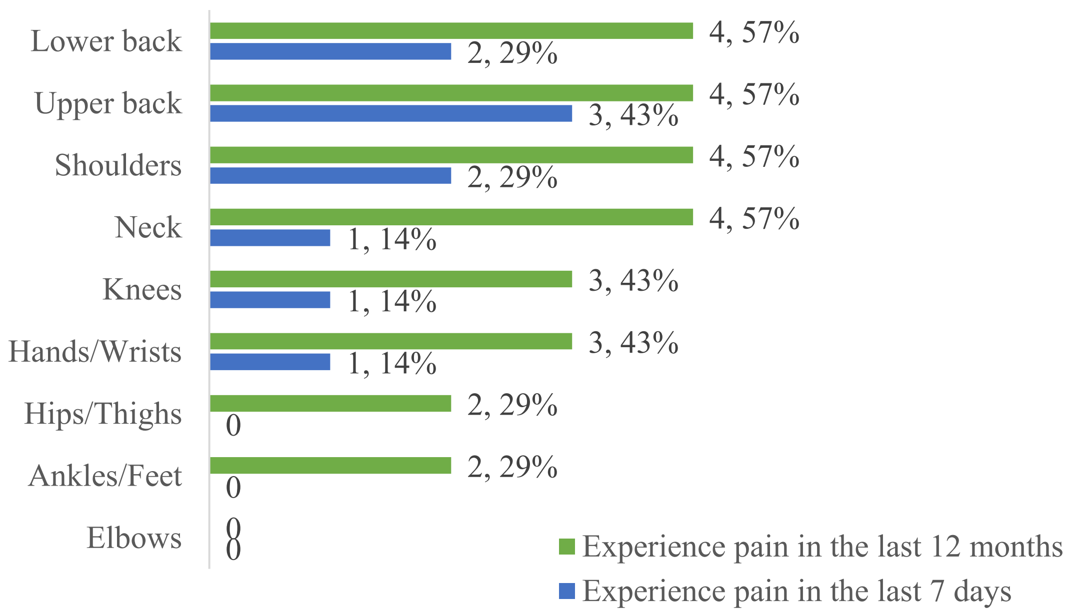


Figure 5.18 Total and percent of workers who experienced pain/discomfort/injury during the last 12 months and 7 days by body area.

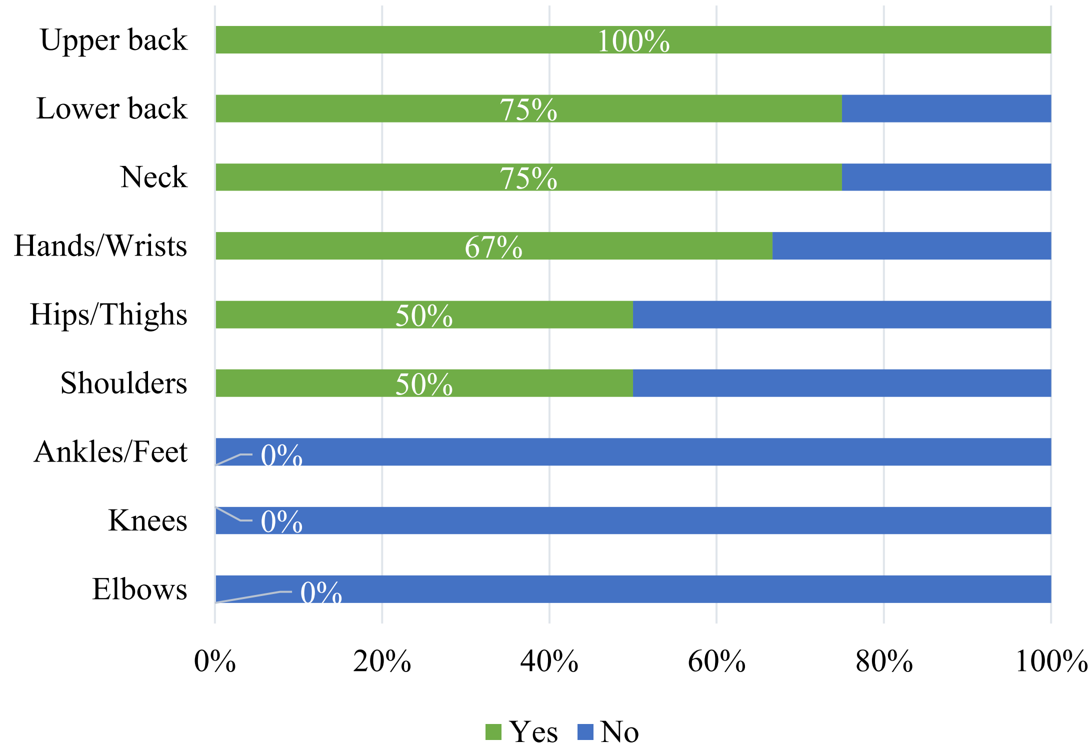


Figure 5.19 Percentage of workers for whom the pain/discomfort prevented them to perform normally at work.

6 CONCLUSIONS

This study explored biomechanical risks associated with coffee harvesting, specifically in the wrist and fingers. Due to the inability to obtain a larger sample size for various reasons, findings might not be generalizable to the broader agricultural population. Even though the sample is small, participant demographics are in consensus with the reality of the agricultural workers in Puerto Rico, that has a profile of predominantly male, aged and highly experienced aged group. Also, findings related to muscular discomforts suggest lower back as the leading cause of discomfort, which relates to typical findings in the literature for this work group. Although participants in this study stated that coffee harvesting is easier to perform than other agricultural tasks, this activity conveys a potential ergonomic risk to the harvester due to the hand activity level or exertion frequency. This is observed with the values of the combinations of NPF and HAL is over the AL line, indicating a risk of development of MSDs.

Results of the postural analysis overall suggest that the task of harvesting coffee should be thoroughly investigated due to the postures assumed. In particular the task should be redesigned considering the limitations posed by the steep terrain, type of crop and worker demographic. These results also suggest that the type of harvesting combined with the use of a bag to harvest or the height of the tree also influences the RULA scoring, suggesting that the use of a harvesting bag and the height of the tree above 6 feet or below 4 feet, pose a MSD risk to the worker.

Finally, this study evaluated hand forces exerted during coffee harvesting using a pressure mapping glove. Statistical analysis for each sensor, placed on the dominant hand of a worker, demonstrated that each person has its own way of executing hand movements during the task and as a consequence there are variations between forces exerted in different regions of the hand and by harvesting method. Based on this study, the forces exerted on the sensors were from 6 x 10^{-3}N to 21 N for both harvesting methods. Results obtained indicate the most active fingers are the index (phalange 2) and thumb fingers (phalange 1) for both methods. When comparing exertion forces and frequency of movements, 82% of the sensors with highest force activity resulted in hand activity levels above the desired Action Limit for the selective method in comparison to 38% of sensors during the scraping method. These results evidence high frequency and exertion duration for the selective harvesting in comparison to the scraping method, with active sensors showing slow steady motions to rapid steady motions with no regular pauses. Even though a model was not developed to predict the hand forces during coffee harvesting, this work provides empirical evidence to suggest that the coffee harvesting task exposes agricultural workers to a risk of developing musculoskeletal disorders based on task duration and repetitiveness.

7 FUTURE WORK

Future work should consider a larger participant sample with a more balanced male to female ratio. Studies should consider the analysis of both hands, when assessing the postures using RULA, as static postures used by the non-dominant hand could contribute to risk of developing MSD's. Also, the design, evaluation and implementation of a tool for coffee harvesting and its biomechanical effects should be considered in a future study. Finally, the use of a different equipment to collect the pressure or forces could be considered for participant comfort and ease of use. In this regard, modeling equipment, such as remote sensors for postural data collection.

With an aging workforce and a harvesting landscape that fosters manual activities, further efforts can be made into worker education and training for the control and prevention of work related MSD. In addition, there is a need to strengthen the collaboration amongst agricultural programs in the island and engineering programs to evaluate harvesting practices, work methods and support ergonomic interventions in harvest activities.

REFERENCES

Aldien, Y., Welcome, D., Rakheja, S., Dong, R., & Boileau, P.-E. (2005). Contact pressure distribution at hand–handle interface: role of hand forces and handle size. *International Journal of Industrial Ergonomics*, *35*(3), 267–286. https://doi.org/10.1016/j.ergon.2004.09.005

American Congress of Governmental Industrial Hygienist. (2017). *Annual Reports for the year 2017: Committees on Threshold Limit Values (TLVs) and Biological Exposure Indices (BEIs)* (pp. 19–21).

Bao, S., Silverstein, B., & Stewart, K. (2013). Evaluation of an ergonomics intervention among Nicaraguan coffee harvesting workers. *Ergonomics*, *56*(2), 166–181. https://doi.org/10.1080/00140139.2012.760753

Bhattacharyya, N., & Chakrabarti, D. (2012). Ergonomic basket design to reduce cumulative trauma disorders in tea leaf plucking operation. *Work*, *41*(1), 1234–1238. https://doi.org/10.3233/WOR-2012-0308-1234

Biddle, E. (2013, March). Business Cases: Supporting PTD Solutions. Retrieved November 5, 2014, from http://library.uprm.edu:2352/abicomplete/docview/1330852567/5F9A2317F4E7417DPQ/3?accountid=28498

Bidiawati, J. R. A., & Suryani, E. (2015). Improving the Work Position of Worker's Based on Quick Exposure Check Method to Reduce the Risk of Work Related Musculoskeletal Disorders. *Procedia Manufacturing*, *4*, 496–503. https://doi.org/10.1016/j.promfg.2015.11.068

Davis, K. G., & Kotowski, S. E. (2007). Understanding the ergonomic risk for musculoskeletal disorders in the United States agricultural sector. *American Journal of Industrial Medicine*, *50*(7), 501–511. https://doi.org/10.1002/ajim.20479

Department of Labor and Human Resources. (2015). Occupational Injuries and Illnesses Survey. Retrieved from http://www.mercadolaboral.pr.gov/lmi/pdf/OSHS/2013/Occupational%20Injuries%20and%20Illnesses%20Survey.pdf

Dong, H., Barr, A., Loomer, P., & Rempel, D. (2005). The Effects of Finger Rest Positions on Hand Muscle Load and Pinch Force in Simulated Dental Hygiene Work. *Journal of Dental Education*, *69*(4), 453–460.

Duraj, V., Miles, J. A., Meyers, J. M., Faucett, J. A., Janowitz, I. L., Tarter, M. E., … Weber, E. A. (2000). HARVESTING AIDS FOR REDUCING ERGONOMICS RISK FACTORS IN WINE GRAPE HAND HARVESTING. Retrieved from http://ag-ergo.ucdavis.edu/papers/2000AsaeVineInterven.pdf

Flores Ortega, C. A. (2011, March 24). Informe empresa de café. Colegio de Ciencias Agrícolas Estación Experimental Agrícola.

Freund, J., Toivonen, R., & Takala, E.-P. (2002). Grip forces of the fingertips. *Clinical Biomechanics*, *17*(7), 515–520. https://doi.org/10.1016/S0268-0033(02)00043-8

International Coffee Organization - What's New. (2018, May 8). Retrieved May 8, 2018, from http://www.ico.org/

Jin, S., McCulloch, R., & Mirka, G. A. (2009). Biomechanical evaluation of postures assumed when harvesting from bush crops. *International Journal of Industrial Ergonomics*, *39*(2), 347–352. https://doi.org/10.1016/j.ergon.2008.07.005

Kuorinka, I., Jonsson, B., Kilbom, A., Vinterberg, H., Biering-Sørensen, F., Andersson, G., & Jørgensen, K. (1987). Standardised Nordic questionnaires for the analysis of musculoskeletal symptoms. *Applied Ergonomics*, *18*(3), 233–237. https://doi.org/10.1016/0003-6870(87)90010-X

McAtamney, L., & Nigel Corlett, E. (1993). RULA: a survey method for the investigation of work-related upper limb disorders. *Applied Ergonomics*, *24*(2), 91–99. https://doi.org/10.1016/0003-6870(93)90080-S

Middlesworth, M. (n.d.). A Step-by-Step: Rapid Upper Limb Assessment (RULA). Ergonomics Plus.

Monroig Inglés, M. (n.d.). Ecos del café. Retrieved from http://academic.uprm.edu/mmonroig/index.htm

Montgomery, D. C. (2017). *Design and Analysis of Experiments*. John Wiley & Sons.

Naeini, H. S., Karuppiah, K., Tamrin, S. B., & Dalal, K. (2014). Ergonomics in agriculture: An approach in prevention of work-related musculoskeletal disorders (WMSDs). *American Research Institute for Policy Development*, *3*(2), 33–51.

Occupational Safety and Health Administration, & Department of Labor. Regulations (Standards - 29 CFR), Recording and Reporting Occupational Injuries and Illness § 1904.1. Retrieved from https://www.ecfr.gov/

Proma, F. A., & Imrhan, S. N. (2013). Pressure Mapping of the Palm While Handling Liquid in a Pot. *IIE Annual Conference. Proceedings*, 1990–1999.

Thamsuwan, O., Aulck, L., Galvin, K., & Johnson, P. W. (2014). Comparison of Exposure to Repetitive Upper Arm Motions and Non-neutral Upper Arm Postures between Apple Harvesting with Ladders and Mobile Platforms. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *58*(1), 1585–1589. https://doi.org/10.1177/1541931214581330

Villanueva, A., Dong, H., & Rempel, D. (2007). A biomechanical analysis of applied pinch force during periodontal scaling. *Journal of Biomechanics*, *40*(9), 1910–1915. https://doi.org/10.1016/j.jbiomech.2006.09.001

APPENDIX A CONSENT FORM FOR PARTICIPATION AND VIDEO RECORDING INCLUDING CONSENT FOR SURVEY, VIDEO, FORCE MAPPING

HOJA DE CONSENTIMIENTO INFORMADO

Universidad de Puerto Rico
Recinto Universitario de Mayagüez
Departamento de Ingeniería Industrial

A quien le pueda interesar,

Usted ha sido invitado/a a participar en una investigación sobre la postura y fuerzas en el cuerpo durante la actividad de recogido de café. Esta investigación es realizada por Ambar Rodríguez Vélez, estudiante graduada de Ingeniería Industrial de la Universidad de Puerto Rico en Mayagüez. El propósito de esta investigación es estudiar y documentar como el tipo de recogido de café afecta la muñeca y la mano de trabajadores como usted. La duración de su participación sería de hasta 1.5 horas en un día, si es posible evaluar ambos métodos de recogido (raspe o selectivo). De no ser posible obtener datos de ambos métodos en un día, una segunda visita se estaría realizando al final de la cosecha para poder evaluar el segundo método.

Si acepta participar en esta investigación:

1. Se le pedirá usar unos sensores en la mano dominante para que realice el recogido de café durante cinco minutos.
2. Mientras se le colocan los sensores en la mano, se le harán una serie de preguntas para conocer más sobre usted y su experiencia de trabajo.
3. Autoriza el uso de cámaras fotográficas y/o de videos como parte de las evaluaciones que serán realizadas. De usar fotos de los videos, su cara será borrada para mantener su anonimato.
4. Como participante en el estudio, no existe beneficio directo fuera de la compensación que recibirán por su participación.
5. Con la información obtenida, se podrá entender si existe riesgo que pueda afectar potencialmente a los trabajadores como usted y el desarrollo de problemas en la espalda, cuello, piernas, codos, rodillas, hombros, manos y muñecas. En un futuro estos resultados pueden ser utilizados para recomendar cambios a métodos actuales de trabajo que beneficien y protejan la salud y seguridad de los trabajadores agrícolas en las fincas de café.
6. Como compensación por su tiempo, se le entregará $10 en efectivo al completar la recolección de datos con los sensores en el recogido selectivo y raspe.

7. No habrá riesgos adicionales a los riesgos típicos asociados a sus labores agrícolas. Si reconocemos que podría sentir incomodidad en los dedos y manos por el uso del sensor, el cual estará pegado con cinta adhesiva especial a la piel.
8. Su identidad será protegida asignándole un número de identificación. Toda información o datos que puedan identificarlo serán manejados confidencialmente.

Si ha leído este documento y ha decidido participar, por favor entienda que su participación es completamente voluntaria y que usted tiene derecho a retirarse del estudio en cualquier momento, sin ninguna penalidad. Para recibir la compensación debe completar ambas partes del estudio. También tiene derecho a no contestar alguna pregunta en particular. Además, tiene derecho a recibir una copia de esta hoja. Si tiene alguna pregunta o desea más información sobre esta investigación, puede comunicarse con Ambar Rodríguez al (787) 515-8998 o con su supervisora Dra. Cristina Pomales García al 787-832-4040 extensión 3103 o vía correo electrónico a cristina.pomales@upr.edu. También, puede comunicarse con la oficina para el Comité para la Protección de Seres Humanos en la investigación al 787-832-4040, extensión 6277 o 6347.

Su firma en este documento significa que ha decidido participar después de haber leído y discutido la información presentada en esta hoja de consentimiento y que ha recibido copia de este documento.

__________________________ ________________________ ____________________

Nombre de la o el participante Firma Fecha

He discutido el contenido de esta hoja de consentimiento con el/la arriba firmante.

__________________________ ________________________ ____________________

Nombre del investigador(a) Firma Fecha

APPENDIX B MUSCULOSKELETAL DISCOMFORT FORM AND DEMOGRAPHIC QUESTIONS

Instrucciones: Las siguientes preguntas están diseñadas para conocer un poco más sobre usted y sus experiencias en este trabajo. Es importante que sea honesto(a) en sus respuestas. Como parte de esta breve entrevista deseamos conocer si ha tenido problemas (dolor, incomodidad, cosquilleo o adormecimiento) en distintas partes del cuerpo y cómo le ha afectado. Puede utilizar la figura humana para hacer referencia a las distintas partes del cuerpo.

1. ID Participante:______
2. Trabajo que realiza: ______________________________
3. Género: ___Masculino ___Femenino
4. Edad: ____________
5. Estatura: ______ pies _____ pulgadas
6. Peso: ____________
7. ¿Por cuánto tiempo lleva realizando este trabajo? ___________________________________
8. ¿En promedio, cuántas horas de trabajo usted realiza cada semana? ___________________
9. ¿Durante el año, realiza usted alguna otra actividad de agricultura, aparte de la cosecha de café?
   ☐ Sí, ¿Cuál?: ________________________________ ☐ No.
10. Comparado con otras actividades de la agricultura, ¿cuán difícil es realizar esta actividad?
    ☐ Mucho más difícil ☐ Más difícil ☐ Igualmente difícil ☐ Menos difícil ☐ Mucho menos difícil
11. ¿Ha tenido problemas (dolor, incomodidad, adormecimiento) en el último año en el cuello?
    ☐ Sí ☐ No.
    a. Si su respuesta a la pregunta anterior fue sí, ¿le ha prevenido realizar su trabajo normal?
    ☐ Sí ☐ No.
    b. ¿Ha tenido problemas durante los últimos 7 días?
    ☐ Sí ☐ No.

12. ¿Ha tenido problemas (dolor, incomodidad, adormecimiento) en el último año en el área de los hombros?
☐ Sí, hombro derecho. ☐ Sí, hombro izquierdo. ☐ Sí, ambos hombros. ☐ No.
    a. Si su respuesta a la pregunta anterior fue sí, ¿le ha prevenido realizar su trabajo normal?
    ☐ Sí ☐ No.
    b. ¿Ha tenido problemas durante los últimos 7 días?
    ☐ Sí ☐ No.
13. ¿Ha tenido problemas (dolor, incomodidad, adormecimiento) en el último año en el área de los codos?
☐ Sí, codo derecho. ☐ Sí, codo izquierdo. ☐ Sí, ambos codos. ☐ No.
    a. Si su respuesta a la pregunta anterior fue sí, ¿le ha prevenido realizar su trabajo normal?
    ☐ Sí ☐ No.
    b. ¿Ha tenido problemas durante los últimos 7 días?
    ☐ Sí ☐ No.
14. ¿Ha tenido problemas (dolor, incomodidad, adormecimiento) en el último año en el área de las muñecas/manos?
☐ Sí, mano/muñeca derecha. ☐ Sí, mano/muñeca izquierda. ☐ Sí, ambas manos/muñecas. ☐ No.
    a. Si su respuesta a la pregunta anterior fue sí, ¿le ha prevenido realizar su trabajo normal?
    ☐ Sí ☐ No.
    b. ¿Ha tenido problemas durante los últimos 7 días?
    ☐ Sí ☐ No.
15. ¿Ha tenido problemas (dolor, incomodidad, adormecimiento) en el último año en el área superior de la espalda?
☐ Sí ☐ No.
    a. Si su respuesta a la pregunta anterior fue sí, ¿le ha prevenido realizar su trabajo normal?
    ☐ Sí ☐ No.
    b. ¿Ha tenido problemas durante los últimos 7 días?
    ☐ Sí ☐ No.

16. ¿Ha tenido problemas (dolor, incomodidad, adormecimiento) en el último año en la espalda baja?

☐ Sí ☐ No.

a. Si su respuesta a la pregunta anterior fue sí, ¿le ha prevenido realizar su trabajo normal?

☐ Sí ☐ No.

b. ¿Ha tenido problemas durante los últimos 7 días?

☐ Sí ☐ No.

17. ¿Ha tenido problemas (dolor, incomodidad, adormecimiento) en el último año en una o ambas caderas/muslos?

☐ Sí ☐ No.

a. Si su respuesta a la pregunta anterior fue sí, ¿le ha prevenido realizar su trabajo normal?

☐ Sí ☐ No.

b. ¿Ha tenido problemas durante los últimos 7 días?

☐ Sí ☐ No.

18. ¿Ha tenido problemas (dolor, incomodidad, adormecimiento) en el último año en una o ambas rodillas?

☐ Sí ☐ No.

a. Si su respuesta a la pregunta anterior fue sí, ¿le ha prevenido realizar su trabajo normal?

☐ Sí ☐ No.

b. ¿Ha tenido problemas durante los últimos 7 días?

☐ Sí ☐ No.

19. ¿Ha tenido problemas (dolor, incomodidad, adormecimiento) en los el último año en uno o ambos tobillos/pies?

☐ Sí ☐ No.

a. Si su respuesta a la pregunta anterior fue sí, ¿le ha prevenido realizar su trabajo normal?

☐ Sí ☐ No.

b. ¿Ha tenido problemas durante los últimos 7 días?

☐ Sí ☐ No.

Figure B.1 Figura humana para referencia durante la entrevista.

APPENDIX C RAW DATA FROM MUSCULOSKELETAL DISCOMFORT FORM.

Numerical answers were tallied for each of the categorical questions.

Table C.1 Demographic questions responses by participant (Questions 1, 3-10).

Participant	Gender	Height (cm)	Age	Weight (kg)	Years of experience	Hours worked per week	Other activities performed[a]	How difficult is this task compared to others?
1	Male	162.56	54	83.91	35	40	1	Less Difficult
2	Female	170.18	45	78.47	22	37.5	1	Less Difficult
3	Male	157.48	54	75.74	45	37.5	1	Less Difficult
4	Male	167.64	69	66.22	50	30	1	Less Difficult
5	Female	-	66	63.50	55	30	0	Less Difficult
6	Male	177.8	34	74.84	-	7.5	1	Less Difficult
7	Male	177.8	34	78.92	3	35	1	More difficult

a. **No = 0, Yes =1**

Table C.2 Individual answers to experienced pain/discomfort/injuries in the past year in different body areas (Questions11-19).

	Experienced pain/discomfort/injuries in the past year in:								
Participant	**Neck[a]**	**Shoulders[b]**	**Upper back[a]**	**Lower back[a]**	**Elbows[b]**	**Hands/ Wrists[b]**	**Hips/ Thighs[a]**	**Knees[a]**	**Ankles/ Feet[a]**
1	0	0	0	0	0	2	0	0	0
2	0	3	1	1	0	1	1	0	0
3	1	3	1	1	0	0	0	1	1
4	1	2	0	0	0	0	0	0	0
5	0	0	0	1	0	3	0	1	0
6	1	2	1	1	0	0	0	0	0
7	1	0	1	0	0	0	1	1	1
Total	4	4	4	4	0	3	2	3	2

a. No = 0, Yes =1; b. No = 0, Both=1, Left=2, Right=3

Table C.3 Participants who experienced pain/discomfort/injuries that prevented normal work performance (Questions 11a-19a).

Pain/Discomfort/Injuries prevented normal work performance:									
Participant	**Neck[a]**	**Shoulders[a]**	**Upper back[a]**	**Lower back[a]**	**Elbows[a]**	**Hands/Wrists[a]**	**Hips/Thighs[a]**	**Knees[a]**	**Ankles/Feet[a]**
1	0	0	0	0	0	1	0	0	0
2	0	1	1	1	0	1	1	0	0
3	1	1	1	1	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	1	0	1	1	0	0	0	0	0
7	1	0	1	0	0	0	0	0	0
Total	3	2	4	3	0	2	1	0	0

a. **No = 0, Yes =1**

Table C.4 Answers to if they experienced pain/discomfort/injuries in the past 7 days. (Questions 11b-19b).

Experienced pain/discomfort/injuries in the past 7 days in:									
Participant	**Neck[a]**	**Shoulders[a]**	**Upper back[a]**	**Lower back[a]**	**Elbows[a]**	**Hands/Wrists[a]**	**Hips/Thighs[a]**	**Knees[a]**	**Ankles/Feet[a]**
1	0	0	0	0	0	0	0	0	0
2	0	0	1	1	0	0	0	0	0
3	1	1	1	1	0	0	0	1	1
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	1	0	0	0	0	0
7	0	0	0	0	0	0	0	0	1
Total	1	1	2	3	0	0	0	1	2

a. **No = 0, Yes =1**

APPENDIX D RULA SCORES AND ANALYSIS

Table D.1 RULA Scores with Method, Bag, and Tree Height used.

Participant	Method	Bag	Tree	Score
1	1	0	Low	4
1	1	1	Low	7
1	2	0	Low	6
1	2	1	Low	7
2	1	0	Medium	5
3	1	0	Medium	4
3	1	1	Medium	7
4	1	0	High	3
4	1	1	High	6
4	2	0	High	7
4	2	1	High	7
5	1	0	High	3
5	1	1	High	6
5	2	0	High	6
5	2	1	High	7
6	1	0	Low	4
6	1	1	Low	7
6	2	0	Low	4
6	2	1	Low	7
7	2	0	Medium	3
7	2	1	Medium	5

Without basket:

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Picking_Low_NoBag
Workstation ID: P1

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	At/near end of wrist twisting range	2
Upper Arms	-20 to 20	1
Lower Arms	> 90	2
Neck	11 - 20	2
Trunk	0 - 20	2
Legs	Legs/feet not supported + uneven	2

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	2	1	0	3
Neck+Leg+Trunk	3	1	0	4

RULA Grand Score: 4

Recommendation:
Further investigation is needed.

Figure D.1 Result for RULA for participant 1 during selective picking.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Scraping_Low_NoBag
Workstation ID: P1

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Upper Arms	46 to 90	3
Upper Arms	Shoulder is raised	1
Upper Arms	Upper arm is abducted	1
Lower Arms	> 90	2
Neck	11 - 20	2
Trunk	0 - 20	2
Legs	Legs/feet not supported + uneven	2

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	5	1	0	6
Neck+Leg+Trunk	3	1	0	4

RULA Grand Score: 6

Recommendation:
Further investigation and changes are required soon.

Figure D.2 Results of RULA for participant 1 during scraping method.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Picking_M_NoBag
Workstation ID: P3

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Upper Arms	-20 to 20	1
Lower Arms	> 90	2
Lower Arms	Lower arm cross body midline	1
Neck	11 - 20	2
Trunk	21 - 60	3
Legs	Legs/feet well-supported	1

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	2	1	0	3
Neck+Leg+Trunk	4	1	0	5

RULA Grand Score: 4

Recommendation:
Further investigation is needed.

Figure D.3 Results from RULA for participant 2 while selective picking.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Picking_M_NoBag
Workstation ID: P2

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Upper Arms	21 to 45	2
Lower Arms	0 to 90	1
Neck	0 - 10	1
Trunk	21 - 60	3
Trunk	Side Bend	1
Legs	Legs/feet well-supported	1

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	2	1	0	3
Neck+Leg+Trunk	5	1	0	6

RULA Grand Score: 5

Recommendation:
Further investigation and changes are required soon.

Figure D.4 Results from RULA for participant 2 during selective method.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Picking_H_NoBag
Workstation ID: P4

Hand: Left Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Upper Arms	46 to 90	3
Lower Arms	0 to 90	1
Neck	0 - 10	1
Trunk	Neutral	1
Legs	Legs/feet well-supported	1

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	3	1	0	4
Neck+Leg+Trunk	1	1	0	2

RULA Grand Score: 3

Recommendation:
Further investigation is needed.

Figure D.5 Results RULA Participant 4 during selective picking.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Scraping_H_NoBag
Workstation ID: P4

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Wrist	Side Bent	1
Upper Arms	>+90	4
Upper Arms	Shoulder is raised	1
Lower Arms	0 to 90	1
Neck	Exten.	4
Trunk	Neutral	1
Legs	Legs/feet well-supported	1

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	5	1	0	6
Neck+Leg+Trunk	5	1	0	6

RULA Grand Score: 7

Recommendation:
Investigate and change now.

Figure D.6 Results RULA for participant 4 during scraping method.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Picking_H_NoBag
Workstation ID: P5

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	At/near end of wrist twisting range	2
Upper Arms	21 to 45	2
Lower Arms	> 90	2
Neck	11 - 20	2
Trunk	Neutral	1
Legs	Legs/feet well-supported	1

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	3	1	0	4
Neck+Leg+Trunk	2	1	0	3

RULA Grand Score: 3

Recommendation:
Further investigation is needed.

Figure D.7 Results RULA for participant 5 during selective method.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Scraping_H_NoBag
Workstation ID: P5

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Wrist	Side Bent	1
Upper Arms	21 to 45	2
Lower Arms	0 to 90	1
Neck	Exten.	4
Neck	Neck is side bending	1
Trunk	Neutral	1
Trunk	Side Bend	1
Legs	Legs/feet well-supported	1

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	3	1	0	4
Neck+Leg+Trunk	7	1	0	8

RULA Grand Score: 6

Recommendation:
Further investigation and changes are required soon.

Figure D.8 Results RULA for participant 5 during scraping method.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Picking_L_NoBag
Workstation ID: P6

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Upper Arms	46 to 90	3
Lower Arms	0 to 90	1
Neck	0 - 10	1
Trunk	0 - 20	2
Legs	Legs/feet not supported + uneven	2

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	3	1	0	4
Neck+Leg+Trunk	3	1	0	4

RULA Grand Score: 4

Recommendation:
Further investigation is needed.

Figure D.9 Result RULA for participant 6 during selective method.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Scraping_L_NoBag
Workstation ID: P6

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Upper Arms	-20 to 20	1
Lower Arms	0 to 90	1
Neck	> 20	3
Trunk	Neutral	1
Legs	Legs/feet not supported + uneven	2

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	1	1	0	2
Neck+Leg+Trunk	3	1	0	4

RULA Grand Score: 4

Recommendation:
Further investigation is needed.

Figure D.10 Result RULA for participant 6 during scraping method.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Picking_H_NoBag
Workstation ID: P4

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Upper Arms	46 to 90	3
Lower Arms	> 90	2
Neck	0 - 10	1
Trunk	Neutral	1
Legs	Legs/feet well-supported	1

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	3	1	0	4
Neck+Leg+Trunk	1	1	0	2

RULA Grand Score: 3

Recommendation:
Further investigation is needed.

Figure D.11 Results RULA for participant 7 during selective method.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Scraping_M_NoBag
Workstation ID: P7

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Upper Arms	21 to 45	2
Lower Arms	0 to 90	1
Neck	0 - 10	1
Trunk	Neutral	1
Legs	Legs/feet well-supported	1

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	2	1	0	3
Neck+Leg+Trunk	1	1	0	2

RULA Grand Score: 3

Recommendation:
Further investigation is needed.

Figure D.12 Results RULA for participant 7 during scraping method.

With basket:

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Picking_Low_WithBag
Workstation ID: P1

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	At/near end of wrist twisting range	2
Upper Arms	-20 to 20	1
Lower Arms	> 90	2
Neck	11 - 20	2
Trunk	0 - 20	2
Legs	Legs/feet not supported + uneven	2

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	2	1	2	5
Neck+Leg+Trunk	3	1	2	6

RULA Grand Score: 7

Recommendation:
Investigate and change now.

Figure D.13 RULA score for participant 1 with bag during selective method.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Scraping_Low_WithBag
Workstation ID: P1

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Upper Arms	46 to 90	3
Upper Arms	Shoulder is raised	1
Upper Arms	Upper arm is abducted	1
Lower Arms	> 90	2
Neck	11 - 20	2
Trunk	0 - 20	2
Legs	Legs/feet not supported + uneven	2

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	5	1	2	8
Neck+Leg+Trunk	3	1	2	6

RULA Grand Score: 7

Recommendation:
Investigate and change now.

Figure D.14 RULA score for participant 1 with bag during scraping method.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Picking_M_WithBag
Workstation ID: P3

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Upper Arms	-20 to 20	1
Lower Arms	> 90	2
Lower Arms	Lower arm cross body midline	1
Neck	11 - 20	2
Trunk	21 - 60	3
Legs	Legs/feet well-supported	1

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	2	1	2	5
Neck+Leg+Trunk	4	1	2	7

RULA Grand Score: 7

Recommendation:
Investigate and change now.

Figure D.15 RULA score for participant 3 with bag during scraping method.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Picking_H_WithBag
Workstation ID: P4

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Upper Arms	46 to 90	3
Lower Arms	> 90	2
Neck	0 - 10	1
Trunk	Neutral	1
Legs	Legs/feet well-supported	1

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	3	1	2	6
Neck+Leg+Trunk	1	1	2	4

RULA Grand Score: 6

Recommendation:
Further investigation and changes are required soon.

Figure D.16 RULA score for participant 4 with ag during selective method

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Picking_H_WithBag
Workstation ID: P4

Hand: Left Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Upper Arms	46 to 90	3
Lower Arms	0 to 90	1
Neck	0 - 10	1
Trunk	Neutral	1
Legs	Legs/feet well-supported	1

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	3	1	2	6
Neck+Leg+Trunk	1	1	2	4

RULA Grand Score: 6

Recommendation:
Further investigation and changes are required soon.

Figure D.17 RULA score for participant 4 with bag during selective method.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Scraping_H_WithBag
Workstation ID: P4

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Wrist	Side Bent	1
Upper Arms	>+90	4
Upper Arms	Shoulder is raised	1
Lower Arms	0 to 90	1
Neck	Exten.	4
Trunk	Neutral	1
Legs	Legs/feet well-supported	1

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	5	1	2	8
Neck+Leg+Trunk	5	1	2	8

RULA Grand Score: 7

Recommendation:
Investigate and change now.

Figure D.18 RULA score for participant 4 with bag during scraping method.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Picking_H_WithBag
Workstation ID: P5

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	At/near end of wrist twisting range	2
Upper Arms	21 to 45	2
Lower Arms	> 90	2
Neck	11 - 20	2
Trunk	Neutral	1
Legs	Legs/feet well-supported	1

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	3	1	2	6
Neck+Leg+Trunk	2	1	2	5

RULA Grand Score: 6

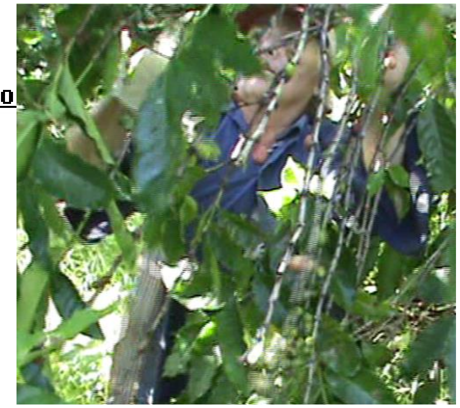
Recommendation:
Further investigation and changes are required soon.

Figure D.19 RULA score for participant 5 with bag during selective method.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Scraping_H_WithBag
Workstation ID: P5

Hand: Right Side



Body Parts	Posture	RULA Sco
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Wrist	Side Bent	1
Upper Arms	21 to 45	2
Lower Arms	0 to 90	1
Neck	Exten.	4
Neck	Neck is side bending	1
Trunk	Neutral	1
Trunk	Side Bend	1
Legs	Legs/feet well-supported	1

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	3	1	2	6
Neck+Leg+Trunk	7	1	2	10

RULA Grand Score: 7

Recommendation:
Investigate and change now.

Figure D.20 RULA score for participant 5 with bag during scraping method

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Picking_L_WithBag
Workstation ID: P6

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Upper Arms	46 to 90	3
Lower Arms	0 to 90	1
Neck	0 - 10	1
Trunk	0 - 20	2
Legs	Legs/feet not supported + uneven	2

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	3	1	2	6
Neck+Leg+Trunk	3	1	2	6

RULA Grand Score: 7

Recommendation:
Investigate and change now.

Figure D.21 RULA score for participant 6 with bag during selective picking.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Scraping_L_WithBag
Workstation ID: P6

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Upper Arms	-20 to 20	1
Lower Arms	0 to 90	1
Neck	> 20	3
Trunk	Neutral	1
Legs	Legs/feet not supported + uneven	2

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	1	1	2	4
Neck+Leg+Trunk	3	1	2	6

RULA Grand Score: 6

Recommendation:
Further investigation and changes are required soon.

Figure D.22 RULA score for participant 6 with bag during scraping method.

Rapid Upper Limb Assessment (RULA)

Analyst: A.Rodriguez
Job Name: Scraping_M_WithBag
Workstation ID: P7

Hand: Right Side

Body Parts	Posture	RULA Score
Wrist	Neutral	1
Wrist	In mid-range of wrist twisting range	1
Upper Arms	21 to 45	2
Lower Arms	0 to 90	1
Neck	0 - 10	1
Trunk	Neutral	1
Legs	Legs/feet well-supported	1

Body Parts	Posture Score	Muscle Score	Force Score	Total
Arm+Wrist	2	1	2	5
Neck+Leg+Trunk	1	1	2	4

RULA Grand Score: 5

Recommendation:
Further investigation and changes are required soon.

Figure D.23 RULA score for participant 7 with bag during scraping method.

APPENDIX E STATISTICAL ANALYSIS AND MINITAB OUTPUTS.

All ANOVA were performed assuming the following

Null hypothesis All means are equal

Alternative hypothesis At least one mean is different

Significance level α = 0.05

Tukey Pairwise comparison was performed with a 95% confidence level for sensors 1 to 24.

Table E.1 ANOVA for sensor 1.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	90.03	15.0056	1384.38	0
Method	1	25.28	25.2757	2331.86	0
Error	9125	98.91	0.0108		
Lack-of-Fit	5	28.41	5.6812	734.9	0
Pure Error	9120	70.5	0.0077		
Total	9132	235.33			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.104112	0.5797	0.5794	0.5789		

Table E.2 Tukey Pairwise Comparison grouping for sensor 1.

Participant	N	Mean	Grouping				
6	211	-1.0051	A				
5	564	-1.0213		B			
1	206	-1.025		B	C		
3	1109	-1.0261		B	C		
7	254	-1.037			C		
4	935	-1.0574				D	
2	758	-1.093					E

Table E.3 ANOVA for sensor 2.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	36.14	6.02	742.95	0
Method	1	6835.44	6835.44	843172.8	0
Error	8768	71.08	0.01		
Lack-of-Fit	5	2.44	0.49	62.39	0
Pure Error	8763	68.64	0.01		
Total	8775	9039.25			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.07343	39.85%	39.76%	39.62%		

Table E.4 Tukey Pairwise Comparison grouping for sensor 2.

Participant	N	Mean	Grouping					
4	1095	-0.9958	A					
3	365	-1.015		B				
1	318	-1.0377			C			
7	1457	-1.0999				D		
5	564	-1.1285					**E**	
6	288	-1.1837						F
2	6	-1.2391						F

Table E.5 ANOVA for sensor 3.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	39.989	6.66482	446.26	0
Method	1	3.604	3.6042	241.33	0
Error	14039	209.668	0.01493		
Lack-of-Fit	6	8.755	1.45919	101.92	0
Pure Error	14033	200.913	0.01432		
Total	14046	249.702			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.122208	16.03%	15.99%	15.88%		

Table E.6 Tukey Pairwise Comparison grouping for sensor 3.

Participant	N	Mean	Grouping				
2	878	1.08302	A				
5	564	1.07422	A				
4	302	0.91949		B			
6	3029	0.90026			C		
1	163	0.8759				D	
3	176	0.8526				D	
7	50	0.7654				D	E

Table E.7 ANOVA for sensor 4.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	193.17	32.195	567.34	0
Method	1	139.2	139.198	2452.98	0
Error	10986	623.42	0.057		
Lack-of-Fit	6	81.17	13.528	273.93	0
Pure Error	10980	542.25	0.049		
Total	10993	907.73			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.238215	31.32%	31.28%	31.20%		

Table E.8 Tukey Pairwise Comparison grouping for sensor 4.

Participant	N	Mean	Grouping			
4	995	-1.1627	A			
6	1923	-1.2352		B		
1	90	-1.2591		B		
2	878	-1.3201			C	
5	460	-1.3503				D
3	45	-1.3804			C	D
7	182	-1.382				D

Table E.9 ANOVA for sensor 5.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	5.14	0.85664	109.9	0
Method	1	9.664	9.66404	1239.82	0
Error	17961	140.001	0.00779		
Lack-of-Fit	6	4.087	0.68113	89.98	0
Pure Error	17955	135.914	0.00757		
Total	17968	161.04			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.088288	13.06%	13.03%	12.97%		

Table E.10 Tukey Pairwise Comparison grouping for sensor 5.

Participant	N	Mean	Grouping			
5	564	1.00299	A			
4	347	0.99425	A			
1	473	0.94809		B		
3	590	0.94402		B	C	
7	697	0.92653		B	C	
2	1430	0.92513			C	
6	3026	0.8936				D

Table E.11 ANOVA for sensor 6.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	6.025	1.0041	80.67	0
Method	1	0.254	0.25363	20.38	0
Error	20748	258.256	0.01245		
Lack-of-Fit	6	20.329	3.38823	295.38	0
Pure Error	20742	237.926	0.01147		
Total	20755	264.286			

S	R-sq	R-sq(adj)	R-sq(pred)
0.111567	2.28%	2.25%	2.19%

Table E.12 Tukey Pairwise Comparison grouping for sensor 6.

Participant	N	Mean	Grouping		
2	878	1.0327	A		
5	564	1.01807	A		
6	3029	0.95202		B	
1	613	0.94493		B	
7	1119	0.9445		B	
3	998	0.90507			C
4	1087	0.89691			C

Table E.13 ANOVA for sensor 7.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	3446	574.3	612	0
Method_t	1	13875	13874.6	14784.97	0
Error	19390	18196	0.9		
Lack-of-Fit	6	1843	307.1	364.07	0
Pure Error	19384	16353	0.8		
Total	19397	36389			

S	R-sq	R-sq(adj)	R-sq(pred)
0.968725	50.00%	49.98%	49.94%

Table E.14 Tukey Pairwise Comparison grouping for sensor 7.

Participant	N	Mean	Grouping				
5	564	1.10286	A				
3	764	0.95949		B			
1	749	0.92667			C		
2	880	0.89545				D	
6	3029	0.89343				D	
4	794	0.89248				D	
7	933	0.8677					E

Table E.15 ANOVA for sensor 8.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	161.688	26.9481	858.8	0
Method	1	2.835	2.8348	90.34	0
Error	16959	532.153	0.0314		
Lack-of-Fit	6	75.072	12.5119	464.06	0
Pure Error	16953	457.082	0.027		
Total	16966	693.897			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.177141	23.31%	23.28%	23.21%		

Table E.16 Tukey Pairwise Comparison grouping for sensor 8.

Participant	N	Mean	Grouping					
5	564	1.17808	A					
2	878	1.10652		B				
4	595	0.981			C			
6	3029	0.94526				D		
1	537	0.8075					E	
3	357	0.7986					E	
7	267	0.59332						F

Table E.17 ANOVA for sensor 9.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	168.85	28.1415	635.89	0
Method	1	22.94	22.942	518.4	0
Error	15921	704.59	0.0443		
Lack-of-Fit	6	104.01	17.3357	459.39	0
Pure Error	15915	600.58	0.0377		
Total	15928	888.17			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.21037	20.67%	20.63%	20.55%		

Table E.18 Tukey Pairwise Comparison grouping for sensor 9.

Participant	N	Mean	Grouping				
2	878	1.32309	A				
5	564	1.11155		B			
6	3029	1.03801			C		
4	276	1.0285			C		
3	579	0.8517				D	
1	82	0.7793				D	
7	829	0.642					E

Table E.19 ANOVA for sensor 10.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	34.5	5.7	914.37	0
Method	1	14259.2	14259.2	2269011	0
Error	17161	107.8	0		
Lack-of-Fit	6	14.4	2.4	440.22	0
Pure Error	17155	93.5	0		
Total	17168	16468.9			

S	R-sq	R-sq(adj)	R-sq(pred)
0.08704	20.66%	20.59%	20.49%

Table E.20 Tukey Pairwise Comparison grouping for sensor 10.

Participant	N	Mean	Grouping					
5	564	1.00483	A					
4	1073	0.97777		B				
3	952	0.92142			C			
6	2560	0.89537				D		
2	388	0.88671				D	E	
1	807	0.87182					E	
7	494	0.85374						F

Table E.21 ANOVA for sensor 11.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	33.7	5.6	308.58	0
Method	1	14440.9	14440.9	792967	0
Error	16537	301.2	0		
Lack-of-Fit	6	51.9	8.7	573.99	0
Pure Error	16531	249.2	0		
Total	16544	16930.8			

S	R-sq	R-sq(adj)	R-sq(pred)
0.13651	19.67%	19.59%	19.47%

Table E.22 Tukey Pairwise Comparison grouping for sensor 11.

Participant	N	Mean	Grouping			
5	564	1.03672	A			
4	580	1.00652		B		
6	3029	0.99189		B		
2	879	0.94112			C	
7	299	0.845				D
1	733	0.8389				D
3	455	0.83365				D

Table E.23 ANOVA for sensor 12.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	103.549	17.2582	549.04	0
Method	1	2.121	2.1212	67.48	0
Error	16901	531.252	0.0314		
Lack-of-Fit	6	67.91	11.3183	412.7	0
Pure Error	16895	463.342	0.0274		
Total	16908	637.476			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.177294	16.66%	16.63%	16.55%		

Table E.24 Tukey Pairwise Comparison grouping for sensor 12.

Participant	N	Mean	Grouping					
2	902	1.19233	A					
5	564	1.08034		B				
4	657	1.0524		B				
7	444	1.0013			C			
6	3029	0.88611				D		
1	962	0.83309					E	
3	365	0.73135						F

Table E.25 ANOVA for sensor 13.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	63.4	10.6	227.1	0
Method	1	15026.2	15026.2	323046.7	0
Error	14121	656.8	0		
Lack-of-Fit	6	179.2	29.9	882.69	0
Pure Error	14115	477.6	0		
Total	14128	17268.7			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.20601	27.90%	27.84%	27.70%		

Table E.26 Tukey Pairwise Comparison grouping for sensor 13.

Participant	N	Mean	Grouping					
2	902	1.19233	A					
5	564	1.08034		B				
4	657	1.0524		B				
7	444	1.0013			C			
6	3029	0.88611				D		
1	962	0.83309					E	
3	365	0.73135						F

Table E.27 ANOVA for sensor 14.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	837.4	139.567	394.78	0
Method	1	251	250.958	709.86	0
Error	13564	4795.3	0.354		
Lack-of-Fit	6	1324.7	220.781	862.48	0
Pure Error	13558	3470.6	0.256		
Total	13571	6091.6			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.594586	21.28%	21.24%	21.15%		

Table E.28 Tukey Pairwise Comparison grouping for sensor 14.

Participant	N	Mean	Grouping			
2	878	-0.5038	A			
6	3029	-1.3472		B		
7	197	-1.4223		B	C	
4	244	-1.62			C	
3	10	-2.017		B	C	D
1	361	-2.5733				D
5	540	-2.7247				D

Table E.29 ANOVA for sensor 15.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	3.6827	0.613781	235.38	0
Method	1	0.5516	0.551571	211.53	0
Error	7679	20.0236	0.002608		
Lack-of-Fit	6	0.3904	0.065061	25.43	0
Pure Error	7673	19.6333	0.002559		
Total	7686	23.9341			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.051065	16.34%	16.26%	16.16%		

Table E.30 Tukey Pairwise Comparison grouping for sensor 15.

Participant	N	Mean	Grouping			
4	355	-1.0145	A			
5	562	-1.0392		B		
3	167	-1.0425		B	C	
7	523	-1.0451			C	
1	92	-1.0483		B	C	D
2	18	-1.0528		B	C	D
6	1173	-1.0565				D

Table E.31 ANOVA for sensor 16.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	3492	582.1	401.92	0
Method	1	15489	15488.6	10695.04	0
Error	14465	20948	1.4		
Lack-of-Fit	6	1586	264.3	197.38	0
Pure Error	14459	19362	1.3		
Total	14472	46949			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
1.20341	55.38%	55.36%	55.33%		

Table E.32 Tukey Pairwise Comparison grouping for sensor 16.

Participant	N	Mean	Grouping				
6	2857	0.95507	A				
2	878	0.91044		B			
4	1044	0.8993		B			
7	389	0.86689			C		
5	396	0.72259				D	
1	184	0.67359					E
3	61	0.6453					E

Table E.33 ANOVA for sensor 17.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	184.49	30.7489	1627	0
Method	1	89.37	89.3696	4728.76	0
Error	19582	370.08	0.0189		
Lack-of-Fit	6	57.29	9.5485	597.59	0
Pure Error	19576	312.79	0.016		
Total	19589	602.38			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.137474	38.56%	38.54%	38.50%		

Table E.34 Tukey Pairwise Comparison grouping for sensor 17.

Participant	N	Mean	Grouping			
6	3029	0.94492	A			
4	423	0.868		B		
3	416	0.84443		B		
5	562	0.78645			C	
2	1893	0.77151			C	
1	556	0.69888				D
7	342	0.59029				E

Table E.35 ANOVA for sensor 18.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	729.8	121.628	159.81	0
Method	1	470.7	470.703	618.45	0
Error	15111	11501	0.761		
Lack-of-Fit	6	1319.6	219.928	326.28	0
Pure Error	15105	10181.4	0.674		
Total	15118	12554.8			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.872411	8.39%	8.35%	8.29%		

Table E.36 Tukey Pairwise Comparison grouping for sensor 18.

Participant	N	Mean	Grouping				
6	2629	-1.1138	A				
3	623	-1.4486		B			
7	370	-1.5188		B	C		
2	925	-1.6009		B	C		
4	391	-1.7302			C		
1	621	-2.5856				D	
5	269	-3.3054					E

Table E.37 ANOVA for sensor 19.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	29.31	4.886	81.48	0
Method	1	288.7	288.704	4814.54	0
Error	5586	334.96	0.06		
Lack-of-Fit	6	25.22	4.203	75.72	0
Pure Error	5580	309.74	0.056		
Total	5593	638.27			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.244877	47.52%	47.45%	47.34%		

Table E.38 Tukey Pairwise Comparison grouping for sensor 19.

Participant	N	Mean	Grouping		
1	74	-1.4173	A		
6	459	-1.4268	A		
5	456	-1.6956		B	
4	452	-1.7186		B	
3	155	-1.7325		B	
7	19	-1.7828		B	
2	44	-2.3003			C

Table E.39 ANOVA for sensor 20.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	13.49	2.2475	42.14	0
Method	1	98.89	98.8869	1854.14	0
Error	8076	430.72	0.0533		
Lack-of-Fit	6	24.09	4.0157	79.7	0
Pure Error	8070	406.62	0.0504		
Total	8083	561.58			

S	R-sq	R-sq(adj)	R-sq(pred)
0.230939	23.30%	23.24%	23.15%

Table E.40 Tukey Pairwise Comparison grouping for sensor 20.

Participant	N	Mean	Grouping		
7	56	-1.4018	A		
4	709	-1.4038	A		
2	949	-1.4173	A		
6	933	-1.424	A		
1	369	-1.5451		B	
3	336	-1.5742		B	C
5	405	-1.6284			C

Table E.41 ANOVA for sensor 21.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	221.7	36.951	444.93	0
Method	1	755.6	755.553	9097.62	0
Error	16912	1404.5	0.083		
Lack-of-Fit	6	109.7	18.29	238.81	0
Pure Error	16906	1294.8	0.077		
Total	16919	2453.5			

S	R-sq	R-sq(adj)	R-sq(pred)
0.288183	42.75%	42.73%	42.70%

Table E.42 Tukey Pairwise Comparison grouping for sensor 21.

Participant	N	Mean	Grouping					
7	434	-1.045	A					
6	2664	-1.132		B				
4	423	-1.1464			C			
1	1090	-1.1518			C	D		
5	532	-1.163				D	E	
3	804	-1.1632					E	
2	1090	-1.2111						F

Table E.43 ANOVA for sensor 22.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	25.4	4.24	418.38	0
Method	1	8446.4	8446.38	834008.9	0
Error	13171	133.4	0.01		
Lack-of-Fit	6	18.3	3.05	348.43	0
Pure Error	13165	115.1	0.01		
Total	13178	12249.4			

S	R-sq	R-sq(adj)	R-sq(pred)
0.13284	28.11%	28.04%	27.96%

Table E.44 Tukey Pairwise Comparison grouping for sensor 22.

Participant	N	Mean	Grouping
6	2355	0.96215	A
1	1559	0.91311	B
4	529	0.85619	C
3	972	0.78135	D
7	249	0.77095	D
5	298	0.72922	E
2	83	0.63755	F

Table E.45 ANOVA for sensor 23.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	5	89.351	17.8702	974.86	0
Method	1	0.082	0.0816	4.45	0.035
Error	12445	228.129	0.0183		
Lack-of-Fit	5	10.431	2.0862	119.21	0
Pure Error	12440	217.698	0.0175		
Total	12451	320.358			

S	R-sq	R-sq(adj)	R-sq(pred)
0.135392	28.79%	28.76%	28.70%

Table E.46 Tukey Pairwise Comparison grouping for sensor 23.

Participant	N	Mean	Grouping
6	2893	1.02443	A
4	423	0.91097	B
1	1532	0.8868	C
2	760	0.81383	D
5	91	0.7857	D E
3	689	0.77941	E

Table E.47 ANOVA for sensor 24.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participant	6	3.192	0.53201	37.62	0
Method_t	1	5.2321	5.23207	369.97	0
Error	4706	66.5513	0.01414		
Lack-of-Fit	5	0.4839	0.09678	6.89	0
Pure Error	4701	66.0674	0.01405		
Total	4713	85.741			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.118919	22.38%	22.27%	22.13%		

Table E.48 Tukey Pairwise Comparison grouping for sensor 24.

Participant	N	Mean	Grouping		
4	343	0.8453	A		
6	1799	0.79319		B	
1	39	0.7787	A	B	
7	113	0.7696		B	
3	4	0.7185	A	B	C
5	39	0.6766			C

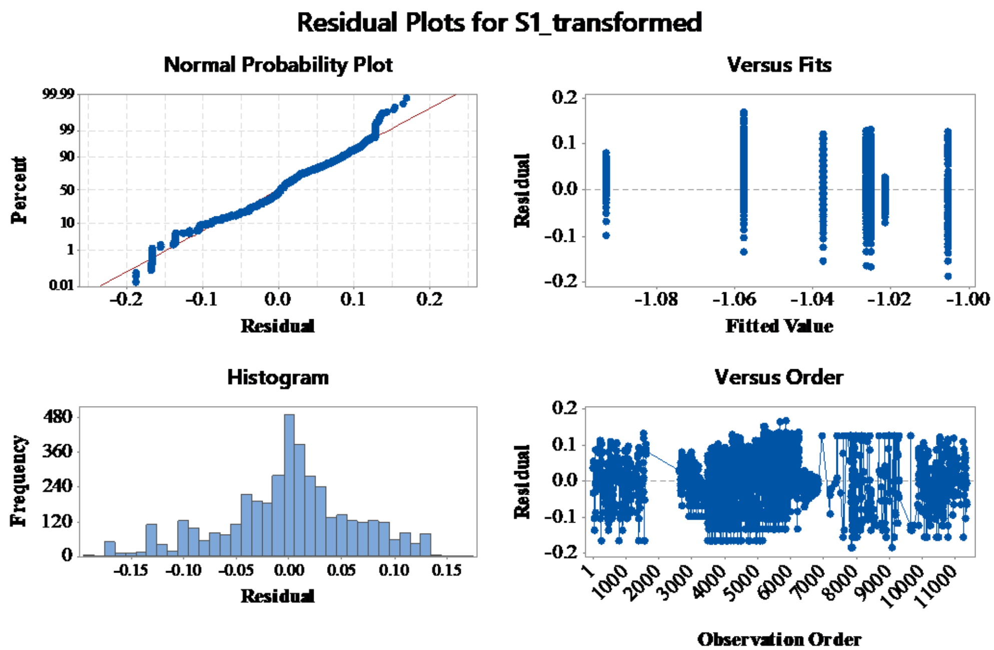


Figure E.1 Residual plot for sensor 1.

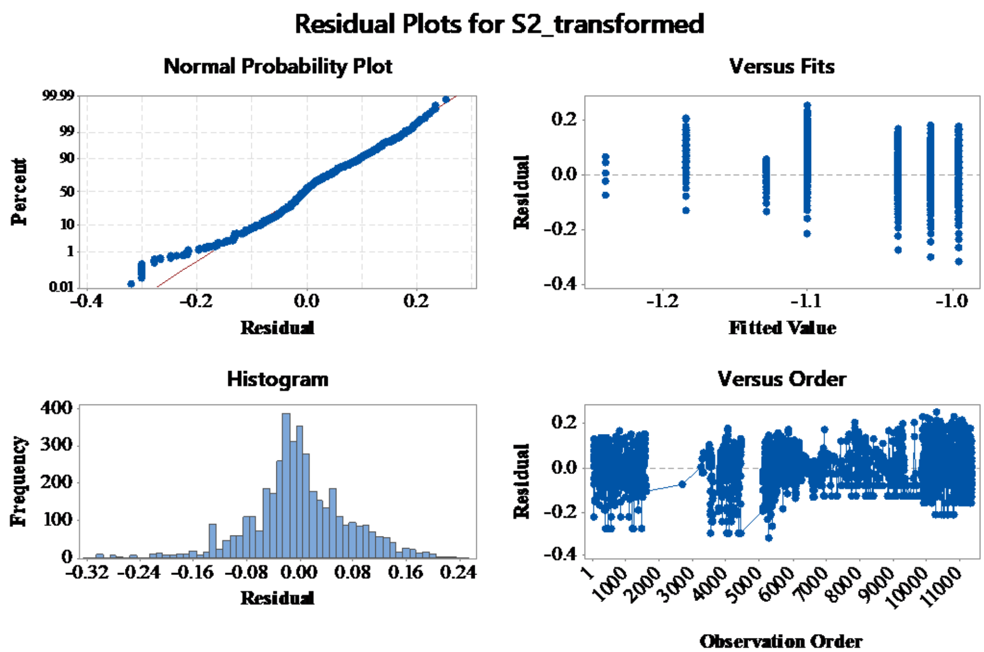


Figure E.2 Residual plot for sensor 2.

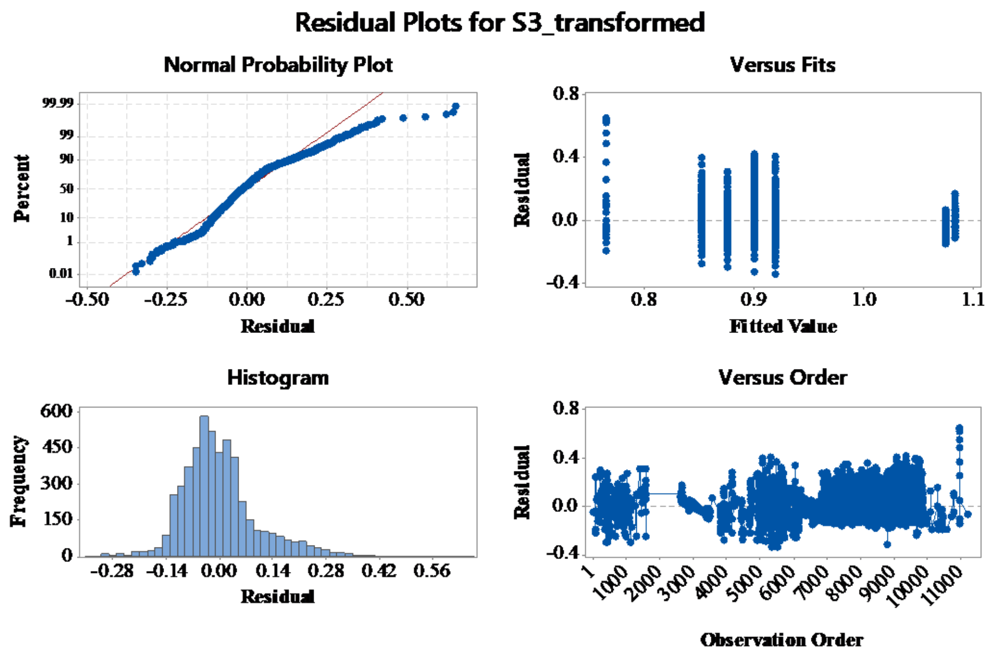


Figure E.3 Residual plot for sensor 3.

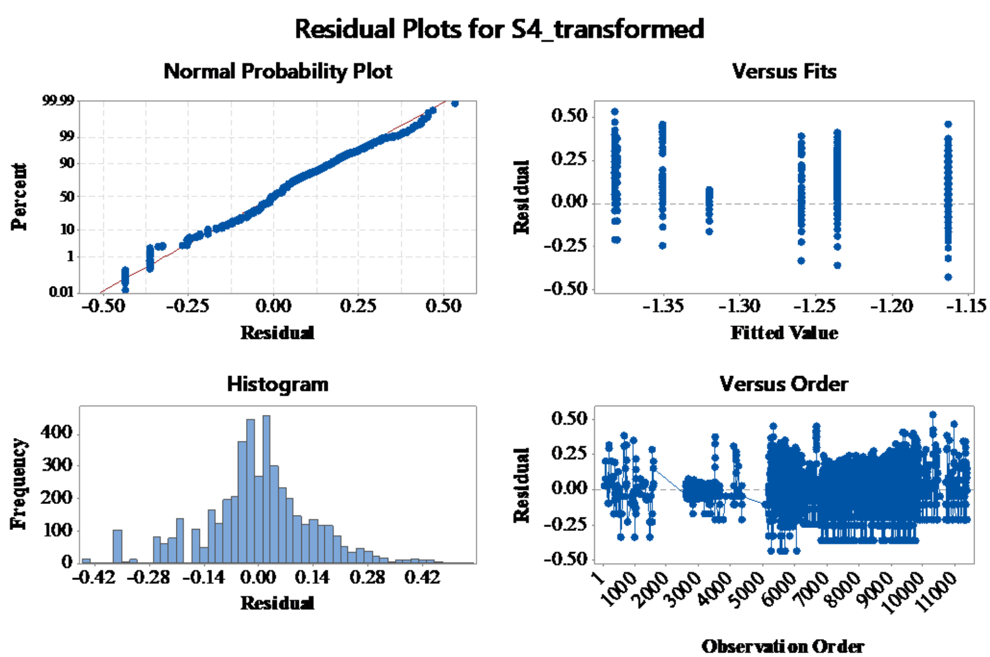


Figure E.4 Residual plot for sensor 4

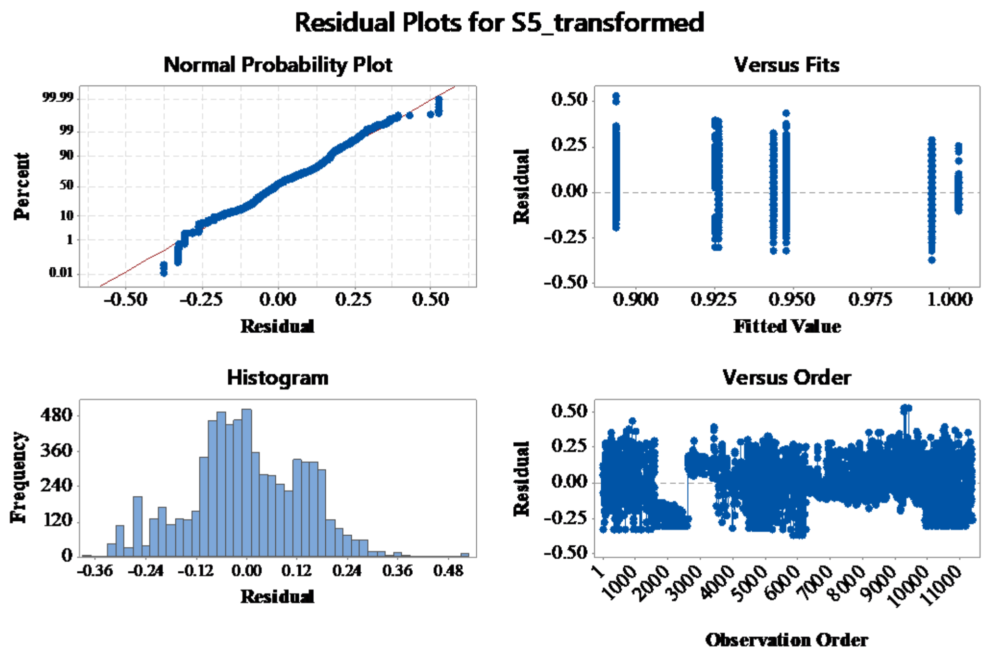


Figure E.5 Residual plot for sensor 5.

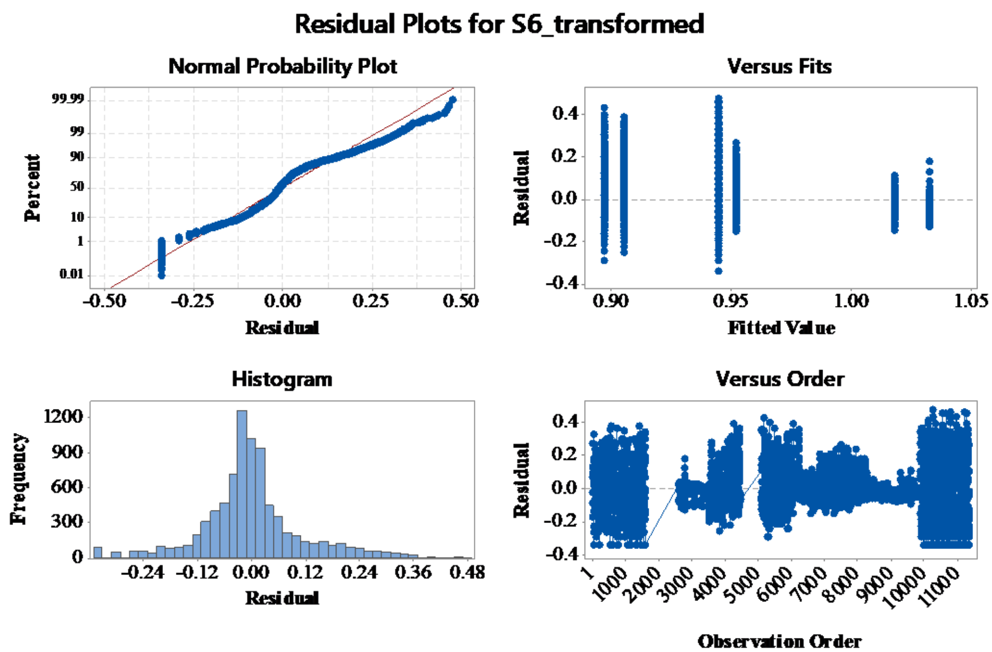


Figure E.6 Residual plot for sensor 6.

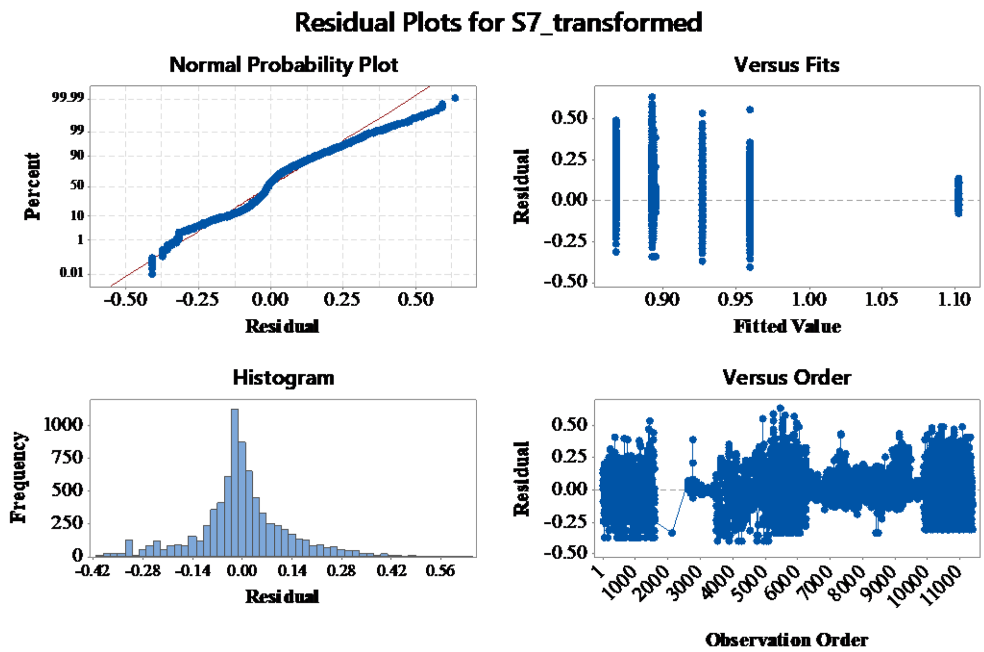


Figure E.7 Residual plot for sensor 7.

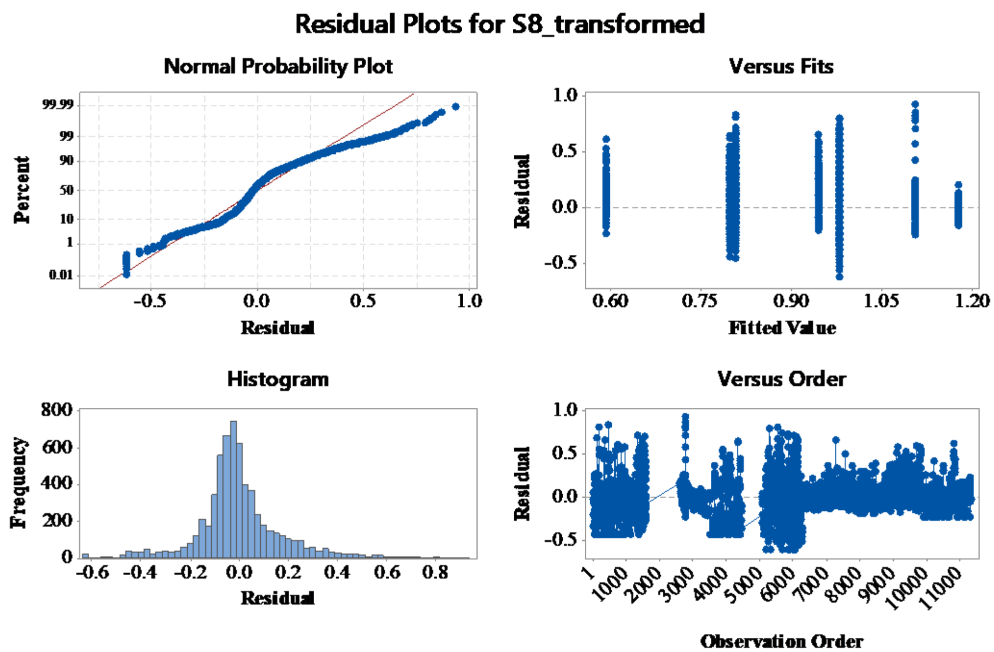


Figure E.8 Residual plot for sensor 8.

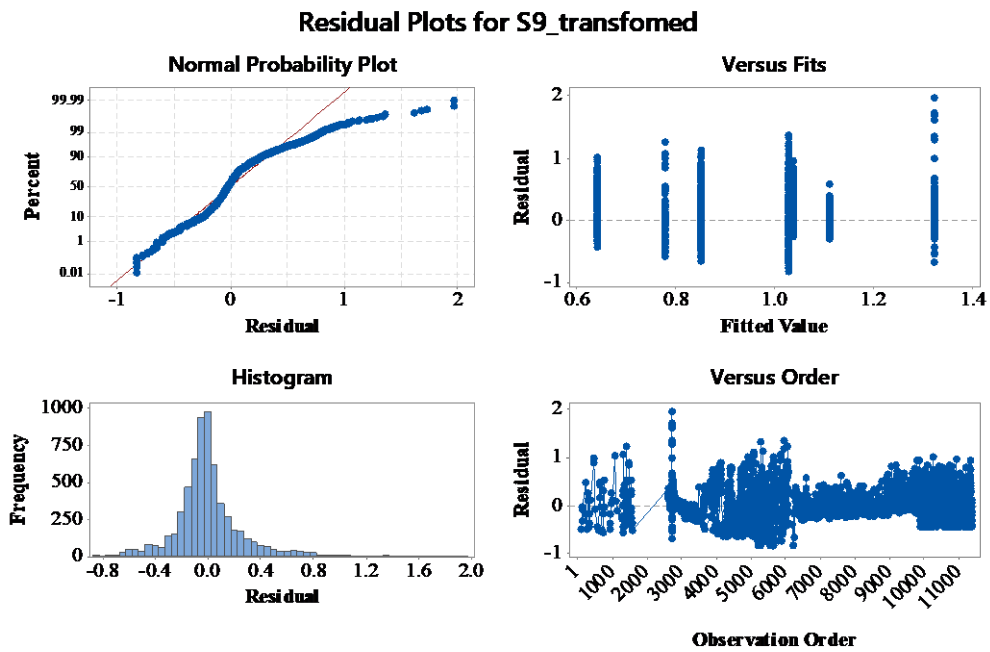


Figure E.9 Residual plot for sensor 9.

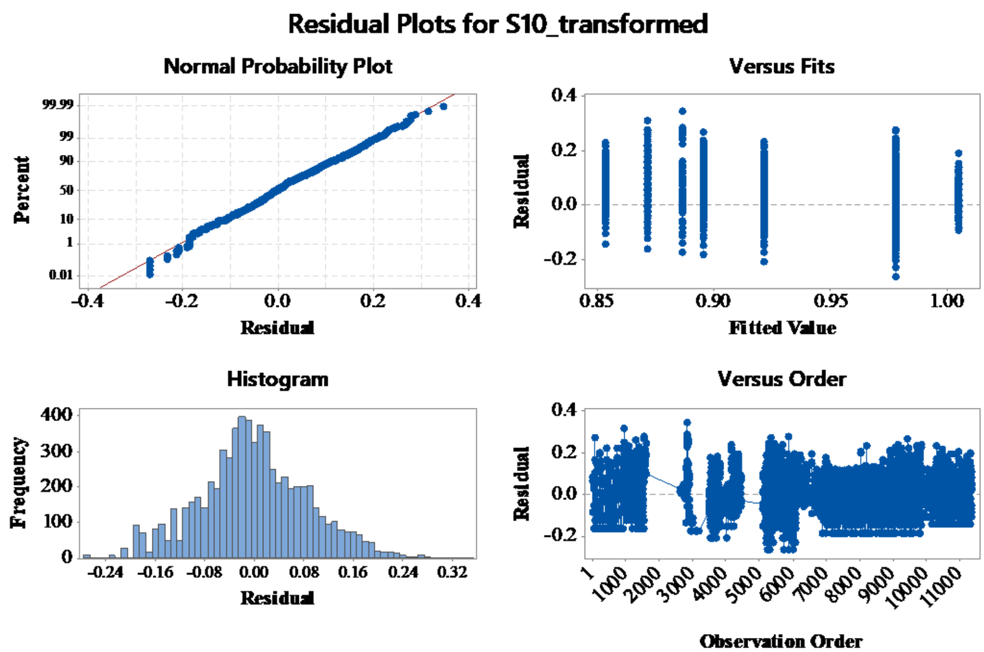


Figure E.10 Residual plot for sensor 10.

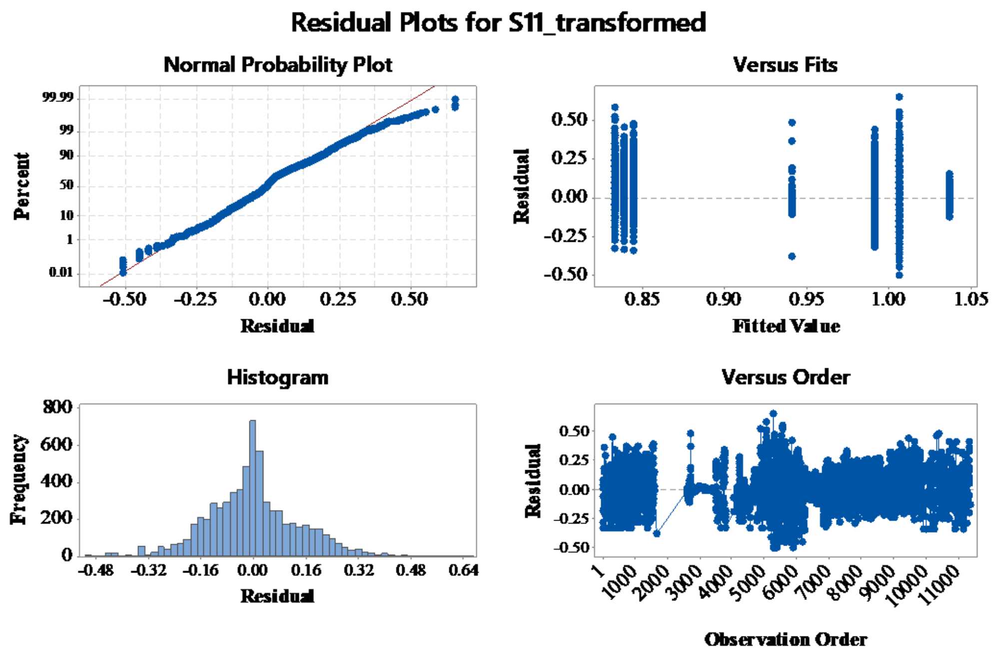


Figure E.11 Residual plot for sensor 11.

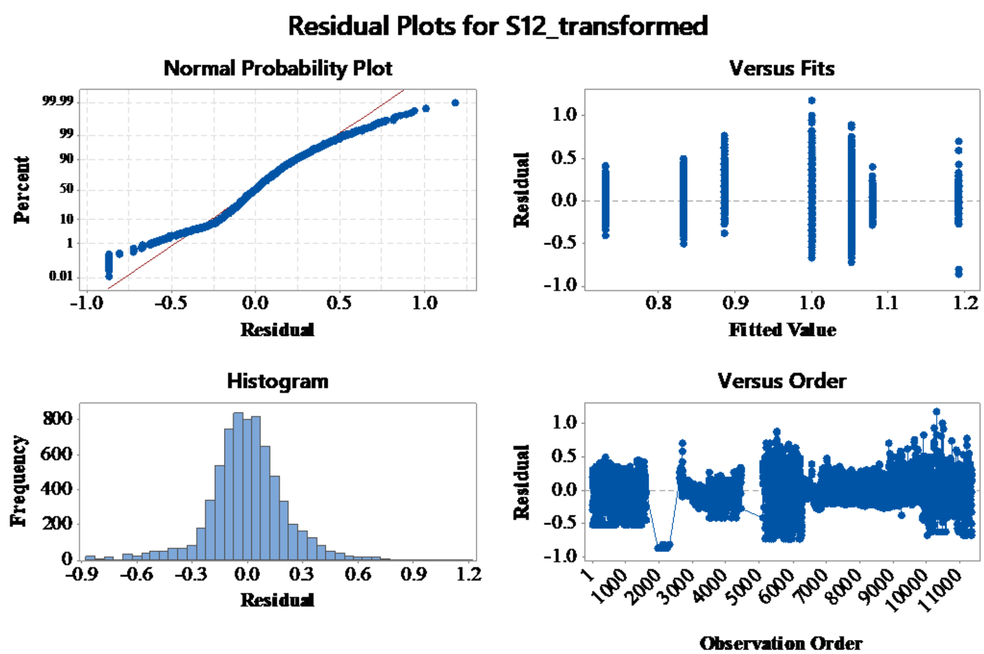


Figure E.12 Residual plot for sensor 12.

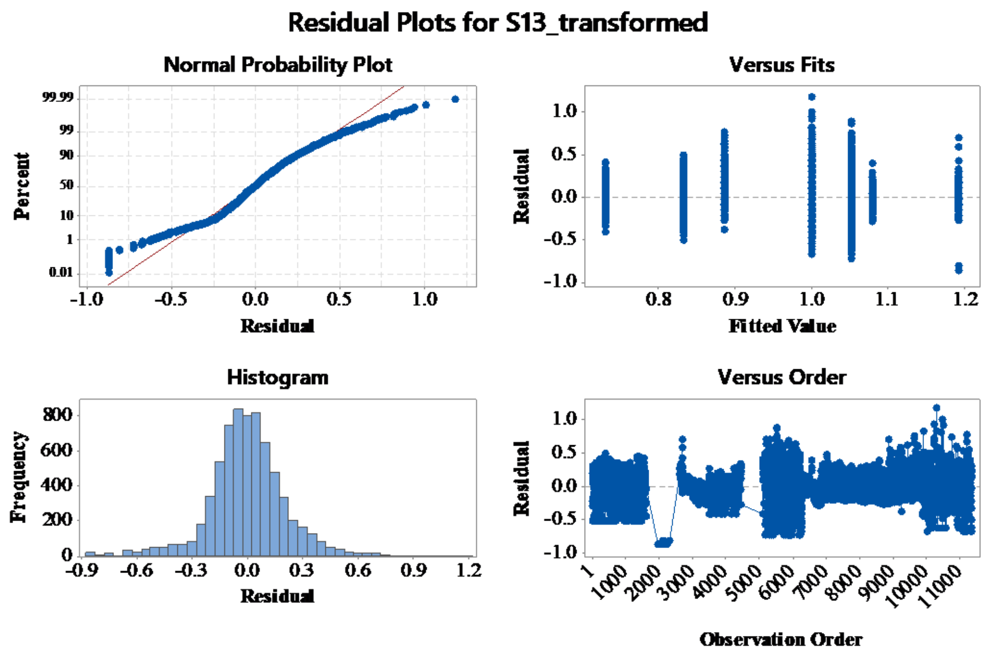


Figure E.13 Residual plot for sensor 13.

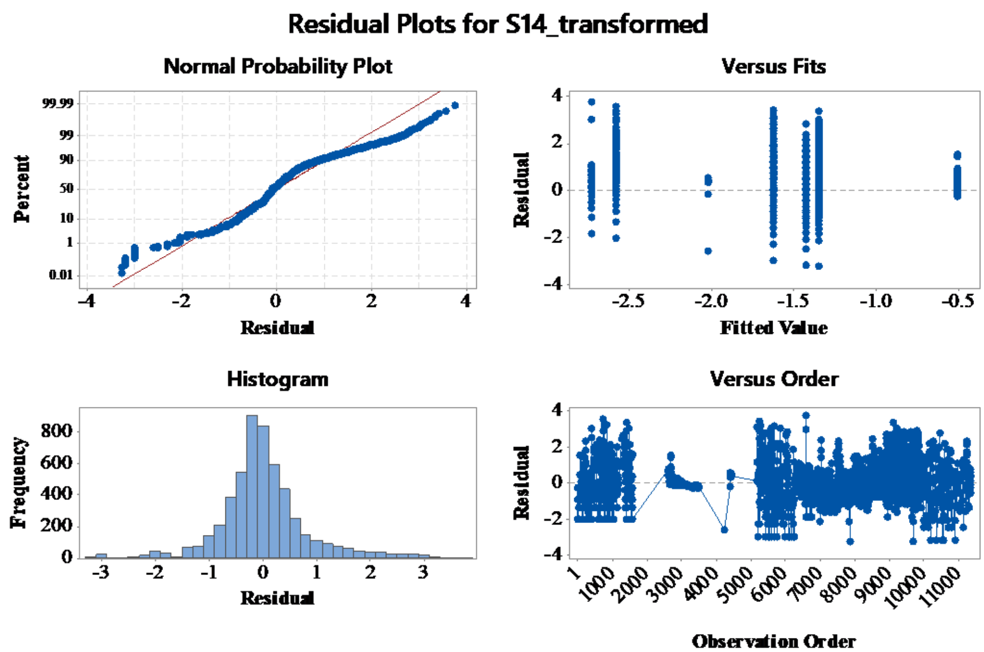


Figure E.14 Residual plot for sensor 14.

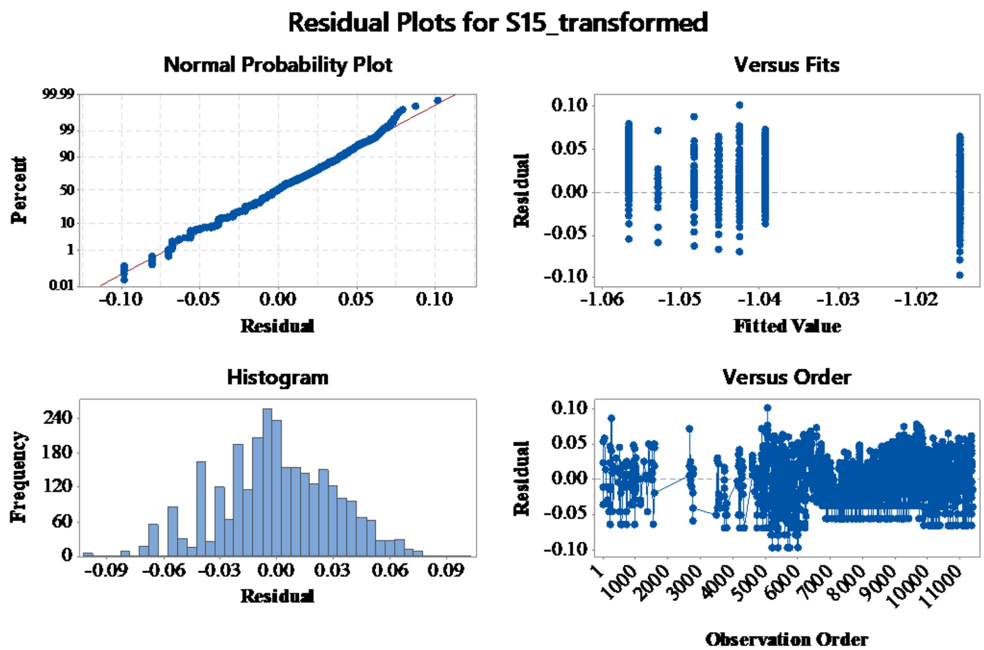


Figure E.15 Residual plot for sensor 15.

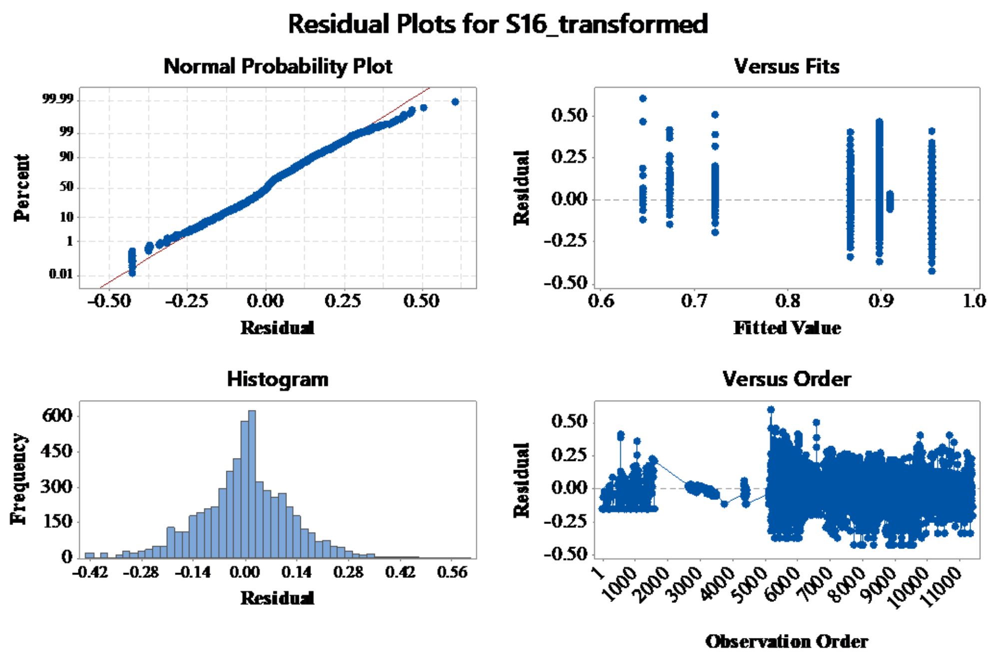


Figure E.16 Residual plot for sensor 16.

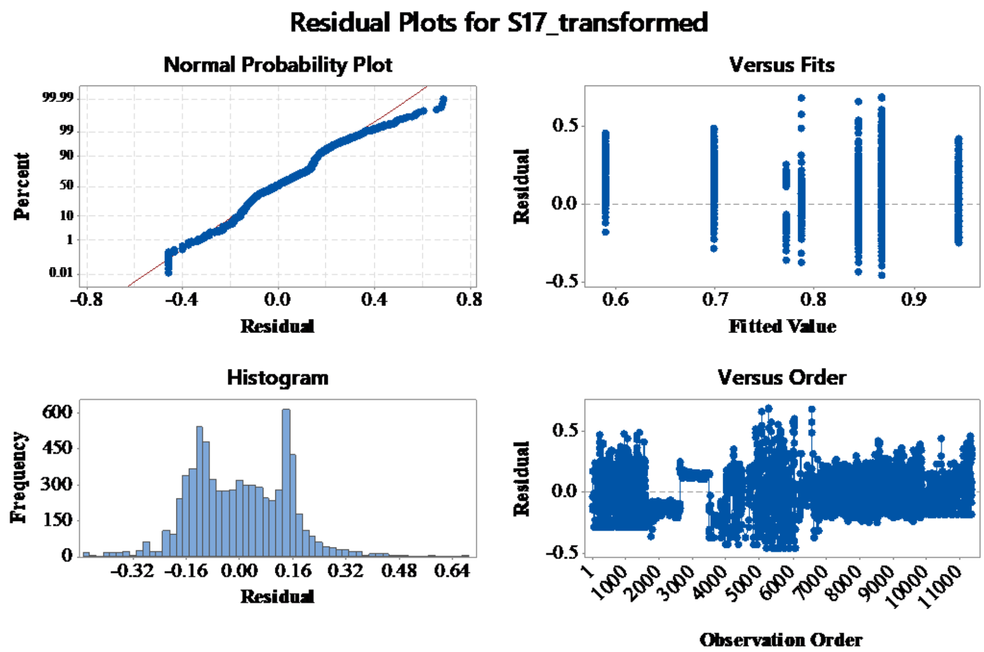


Figure E.17 Residual plot for sensor 17.

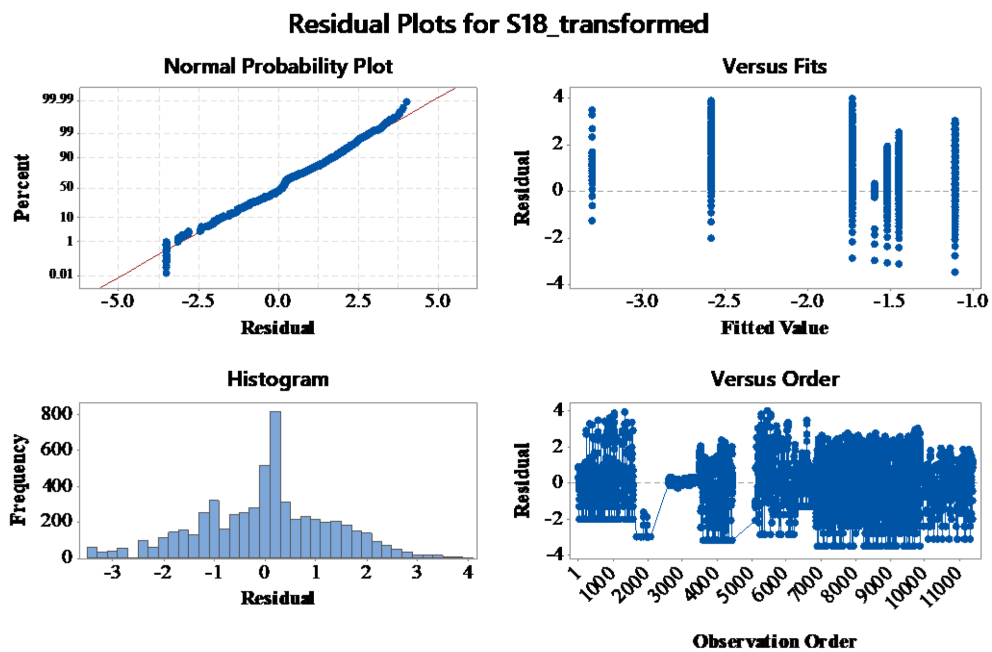


Figure E.18 Residual plot for sensor 18.

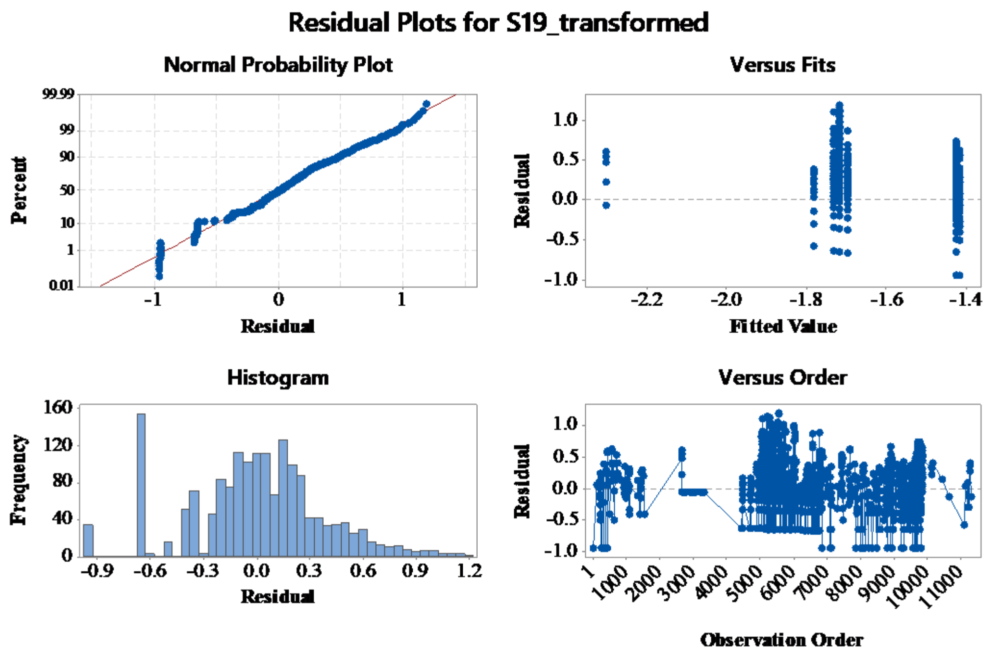


Figure E.19 Residual plot for sensor 19.

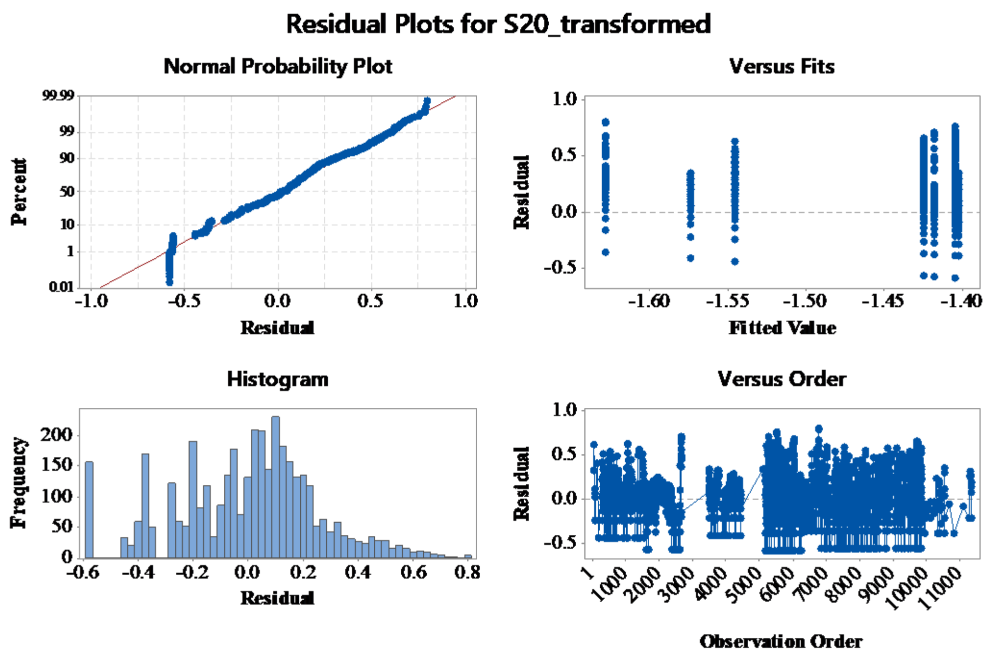


Figure E.20 Residual plot for sensor 20.

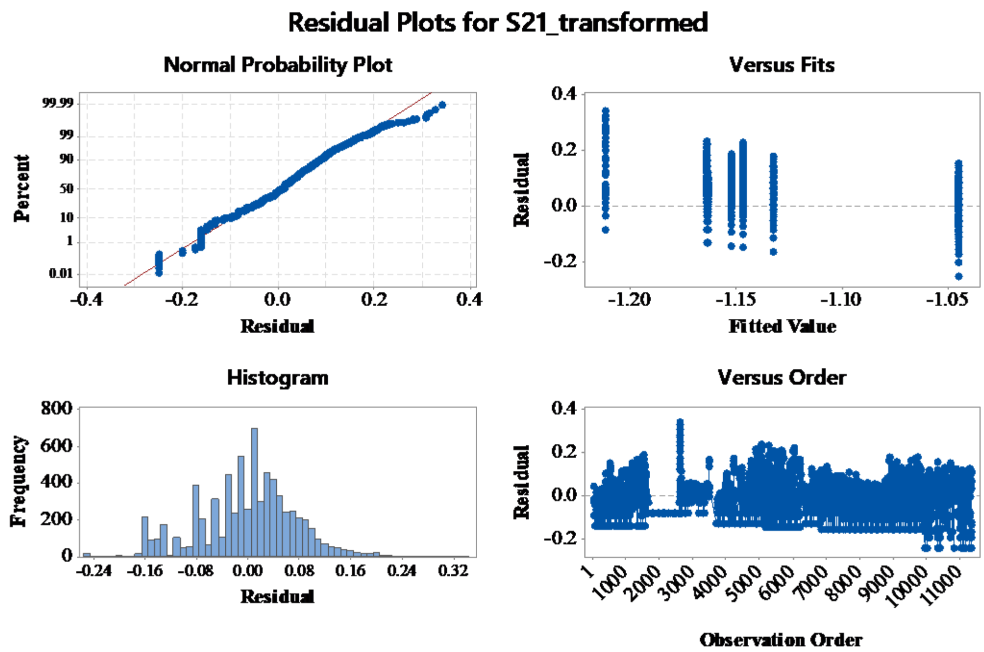


Figure E.21 Residual plot for sensor 21.

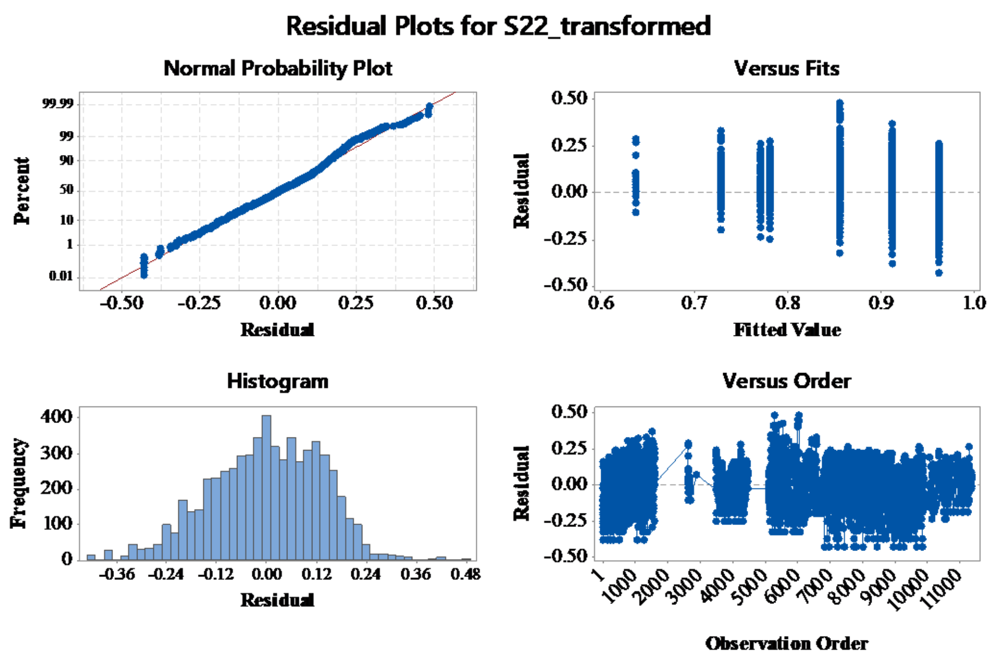


Figure E.22 Residual plot for sensor 22.

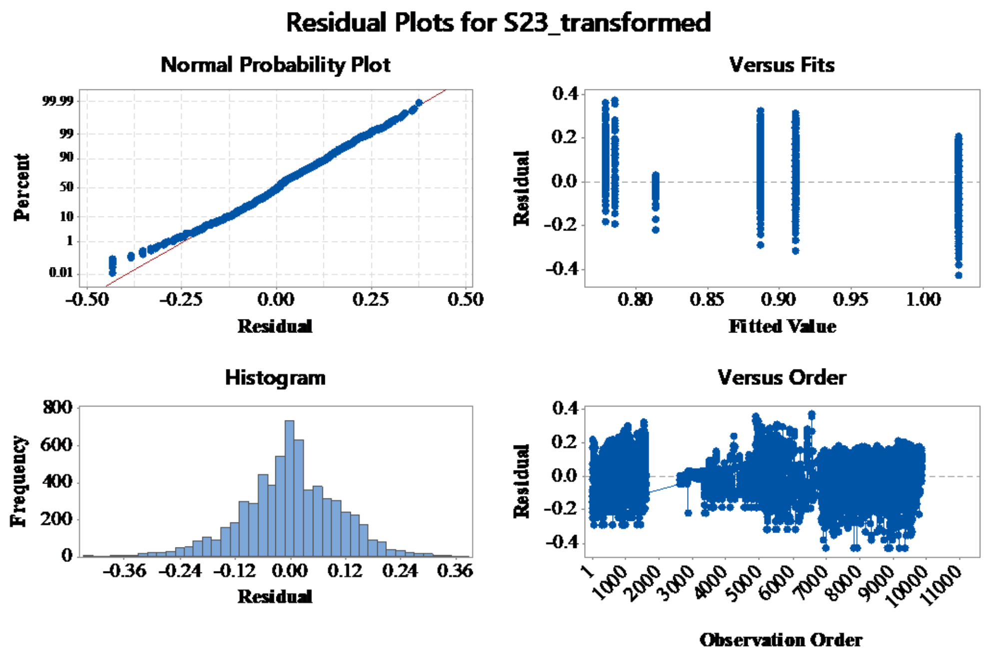


Figure E.23 Residual plot for sensor 23.

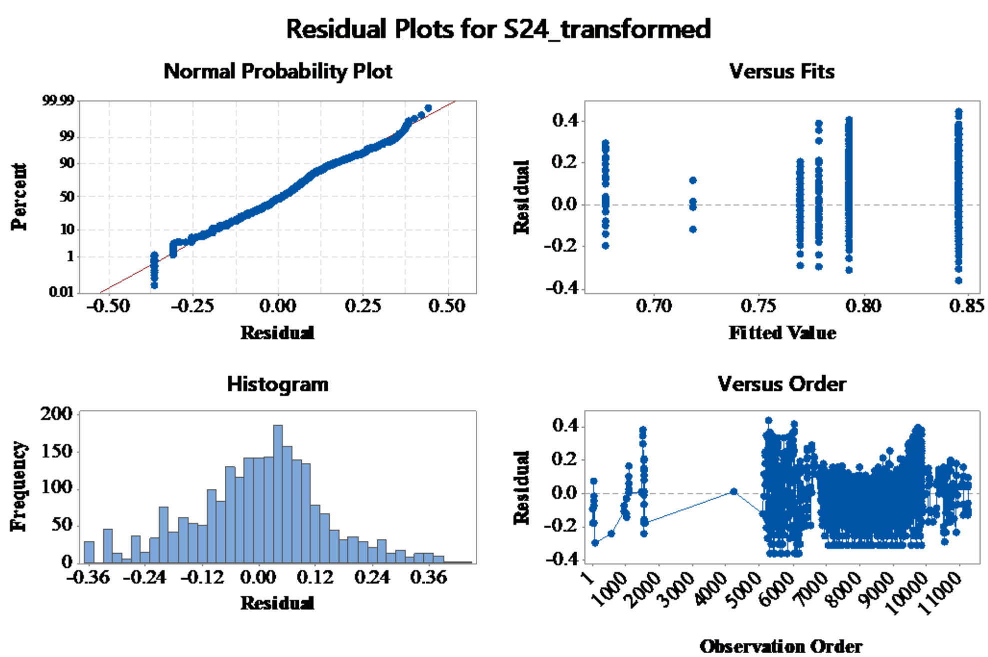


Figure E.24 Residual plot for sensor 24.

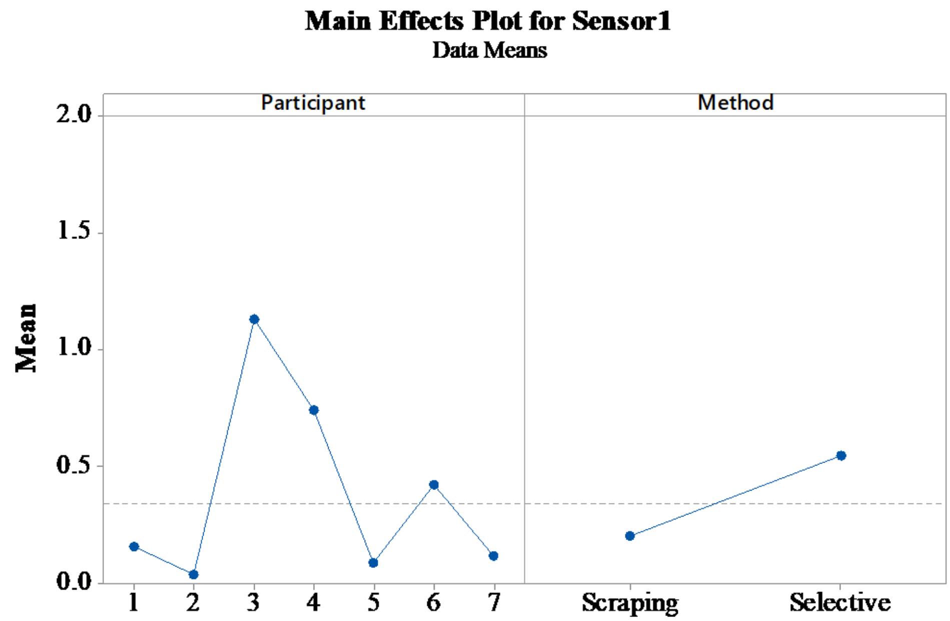


Figure E.25 Main Effect Plot for sensor 1 between participant and method variable.

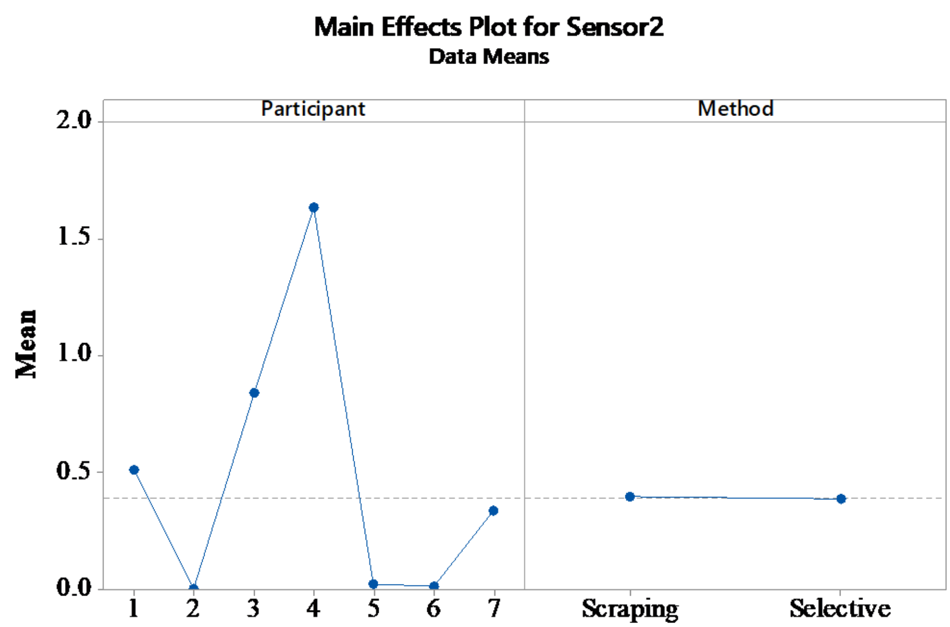


Figure E.26 Main Effect Plot for sensor 2 between participant and method variable.

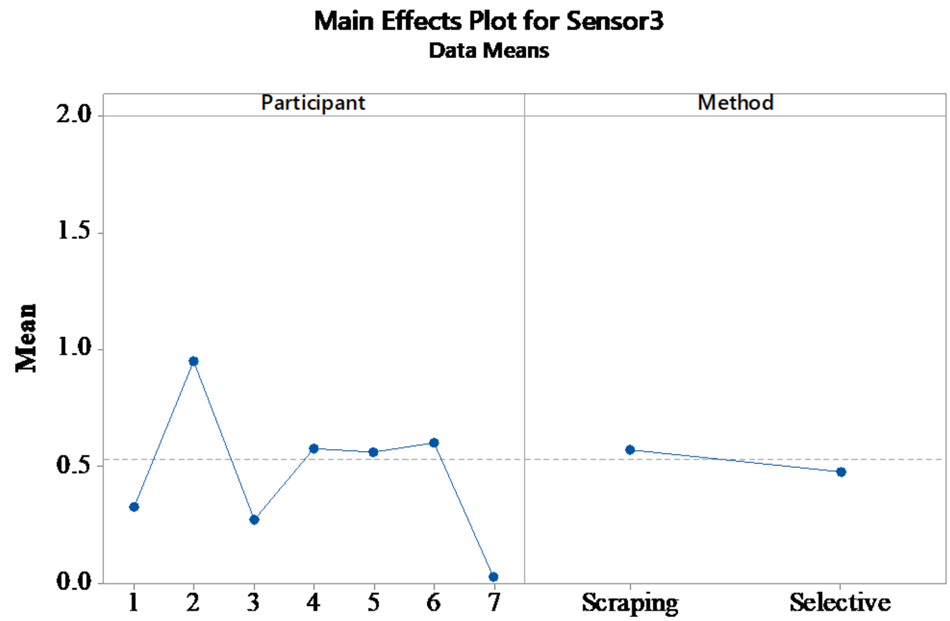


Figure E.27 Main Effect Plot for sensor 3 between participant and method variable.

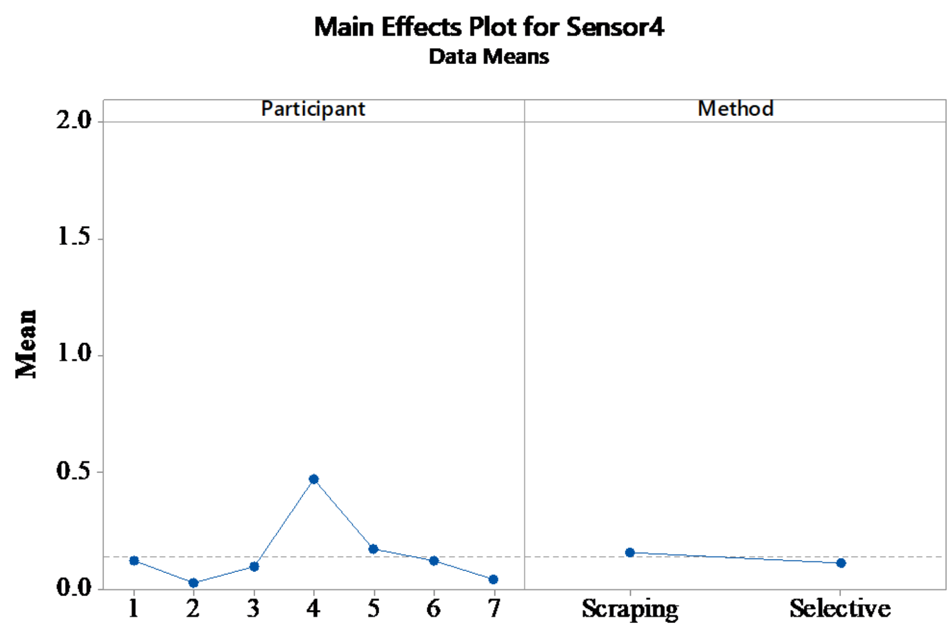


Figure E.28 Main Effect Plot for sensor 4 between participant and method variable.

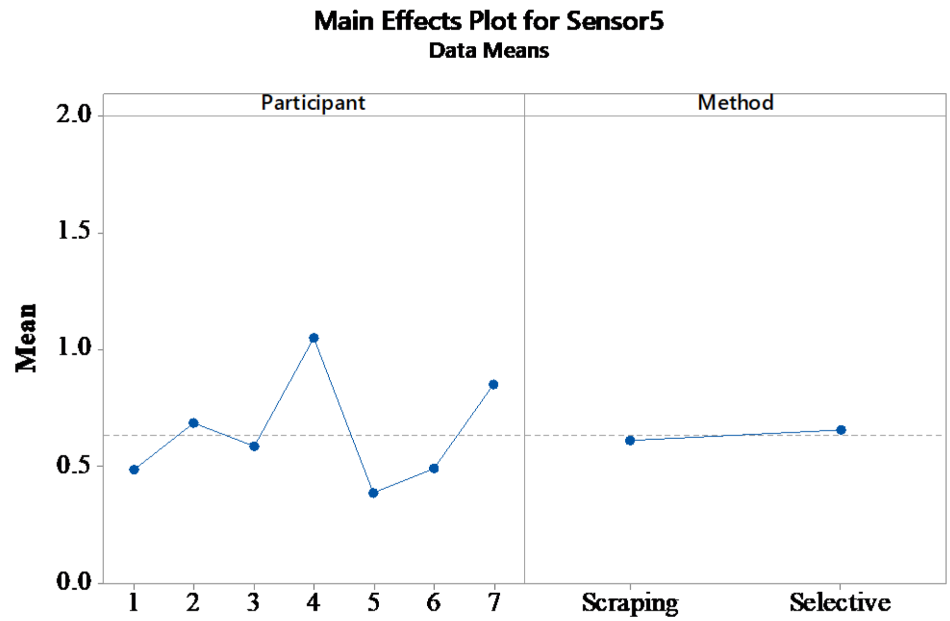


Figure E.29 Main Effect Plot for sensor 5 between participant and method variable.

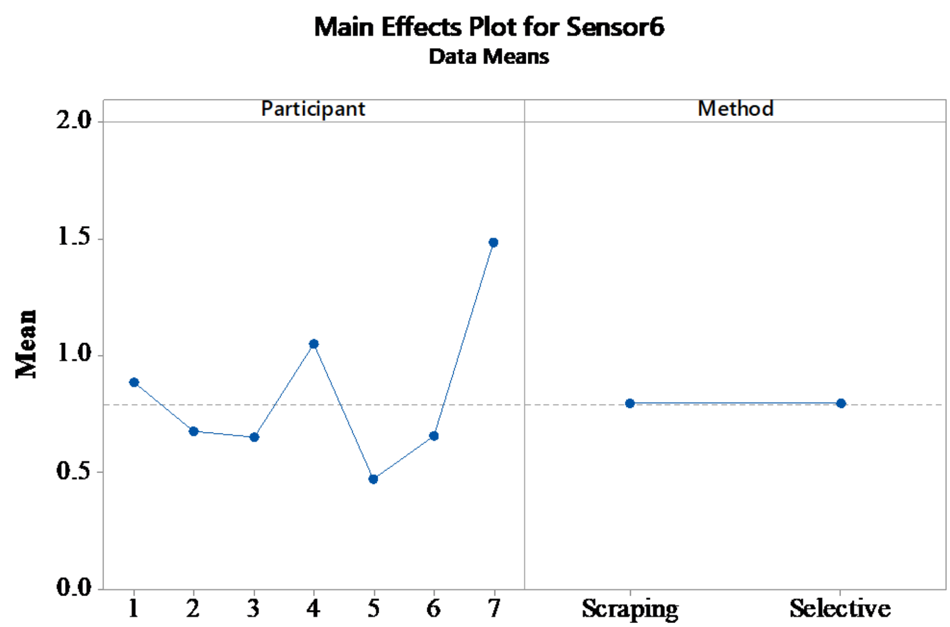


Figure E.30 Main Effect Plot for sensor 6 between participant and method variable.

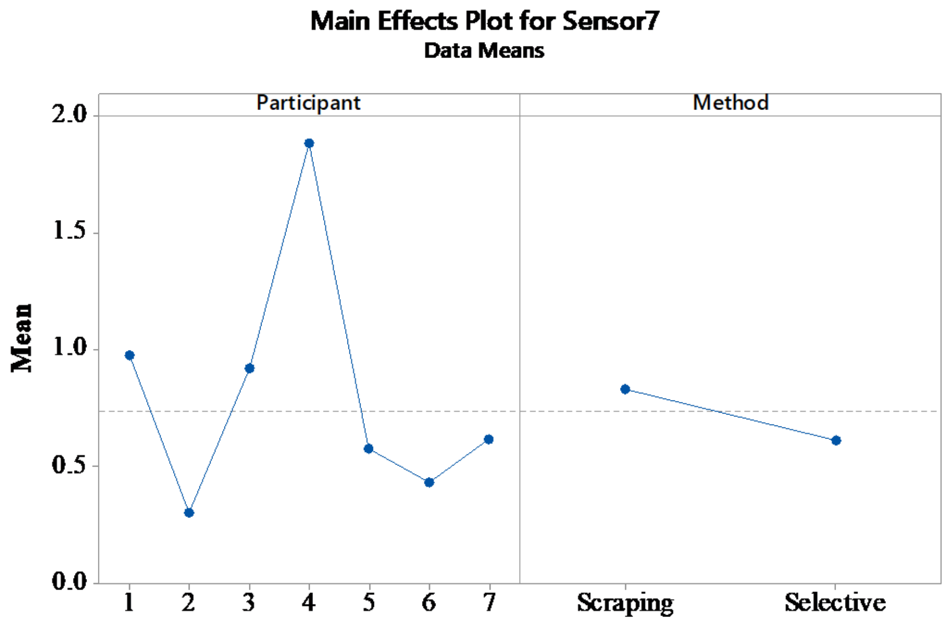


Figure E.31 Main Effect Plot for sensor 7 between participant and method variable.

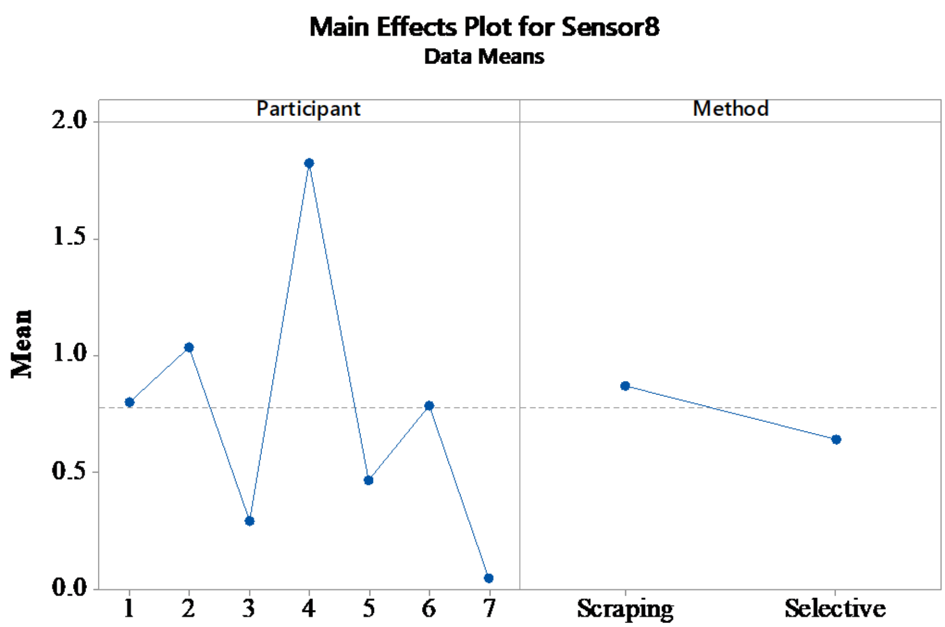


Figure E.32 Main Effect Plot for sensor 8 between participant and method variable.

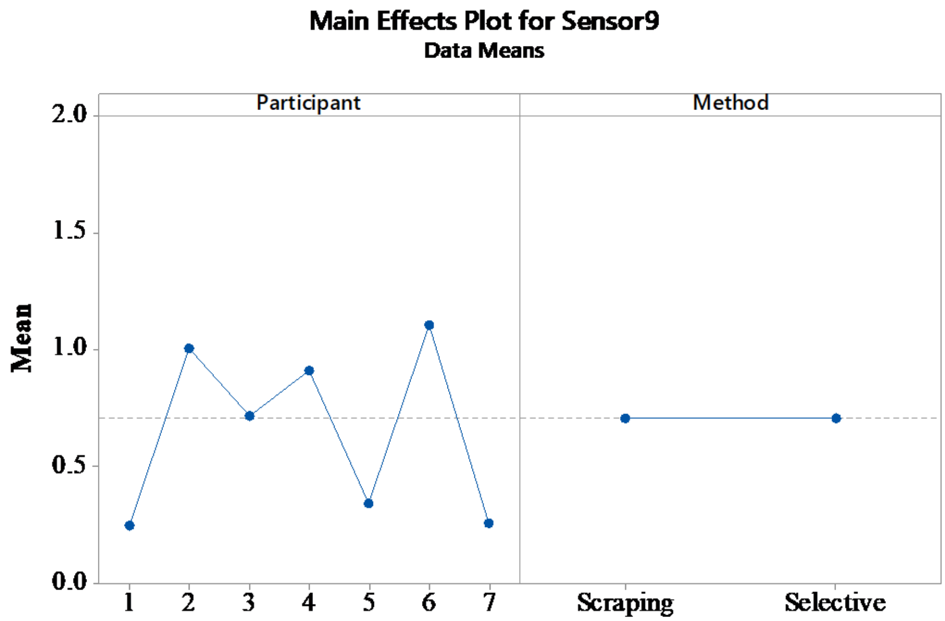


Figure E.33 Main Effect Plot for sensor 9 between participant and method variable.

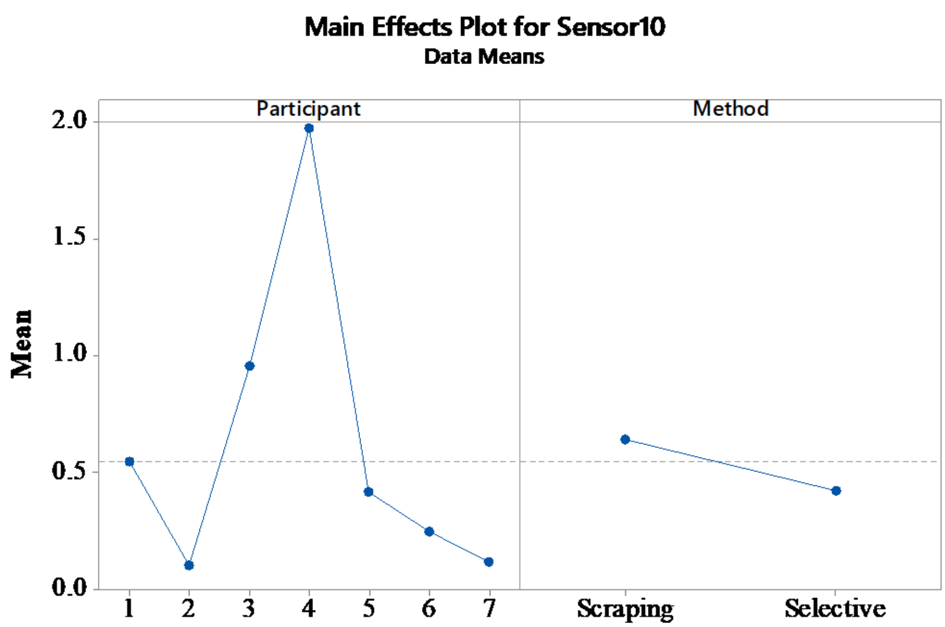


Figure E.34 Main Effect Plot for sensor 10 between participant and method variable.

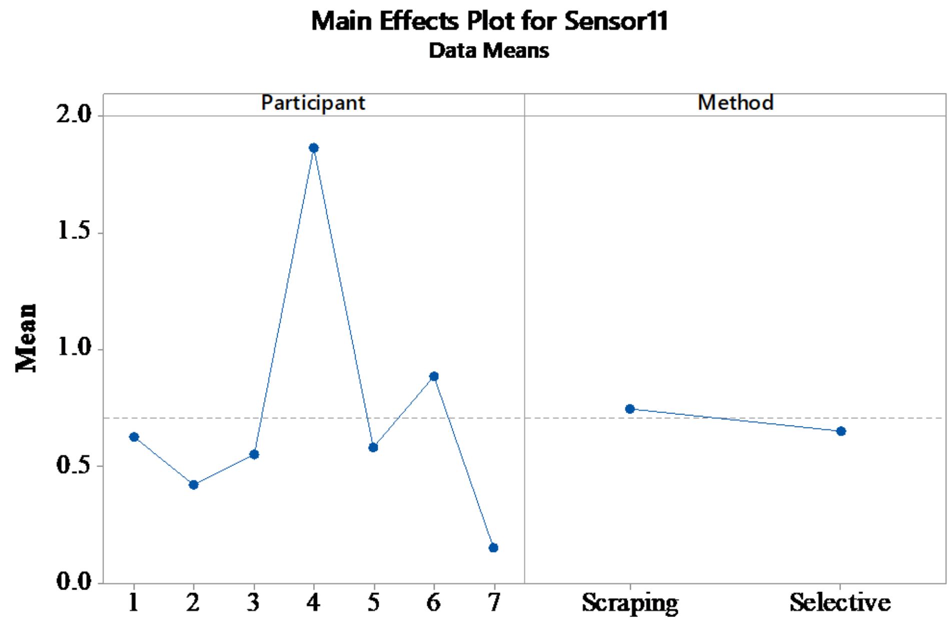


Figure E.35 Main Effect Plot for sensor 11 between participant and method variable.

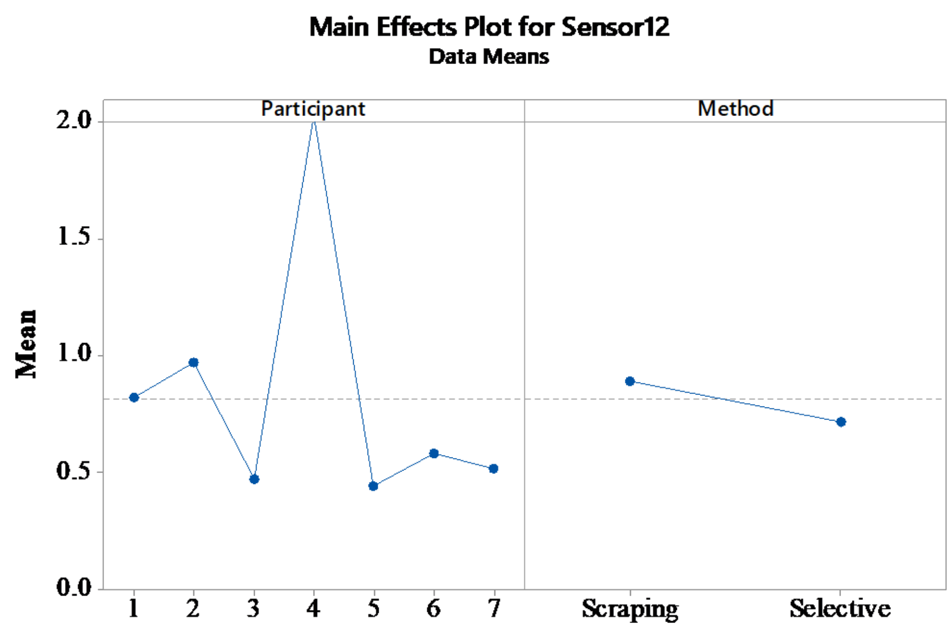


Figure E.36 Main Effect Plot for sensor 12 between participant and method variable.

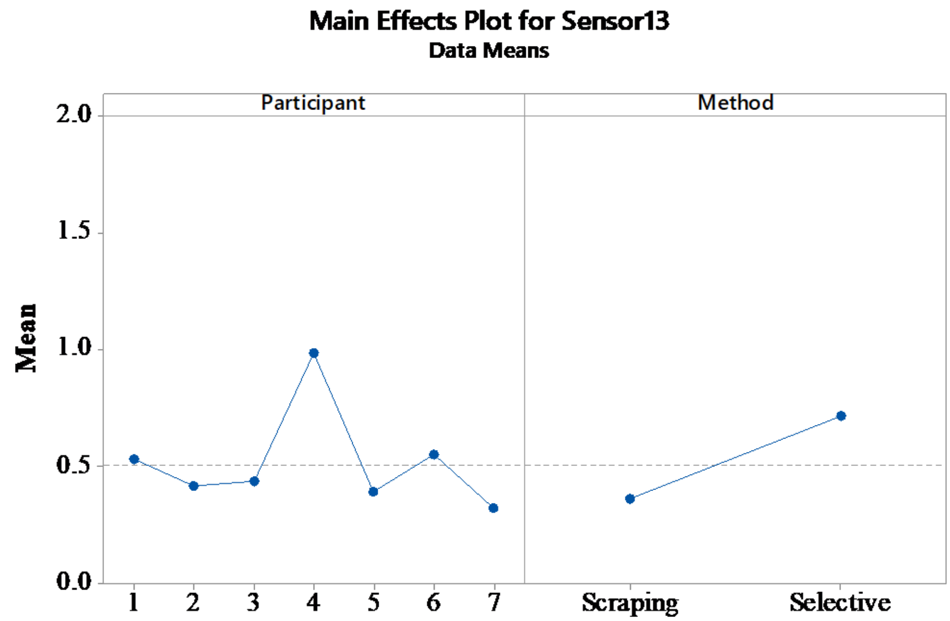


Figure E.37 Main Effect Plot for sensor 13 between participant and method variable.

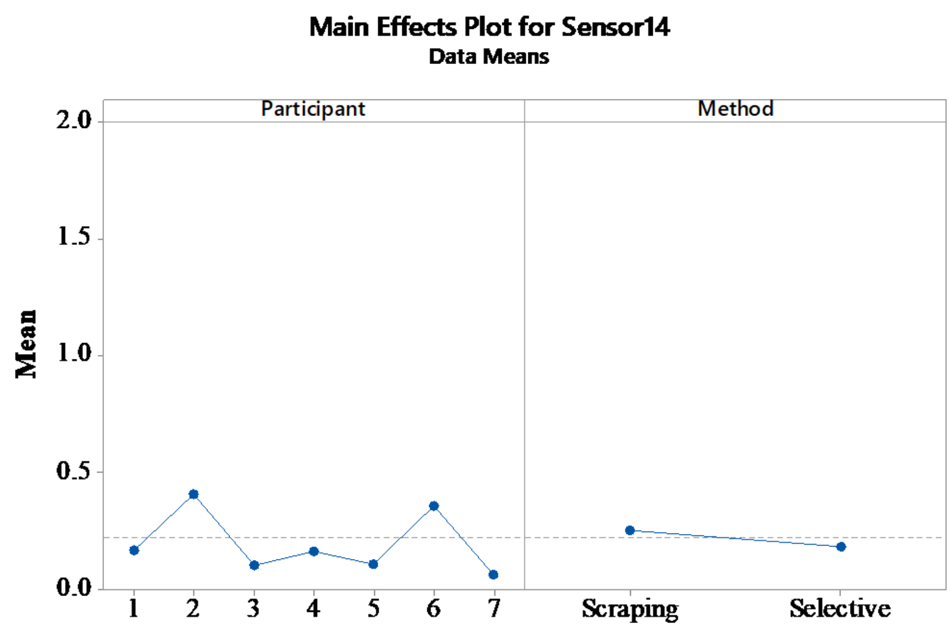


Figure E.38 Main Effect Plot for sensor 14 between participant and method variable.

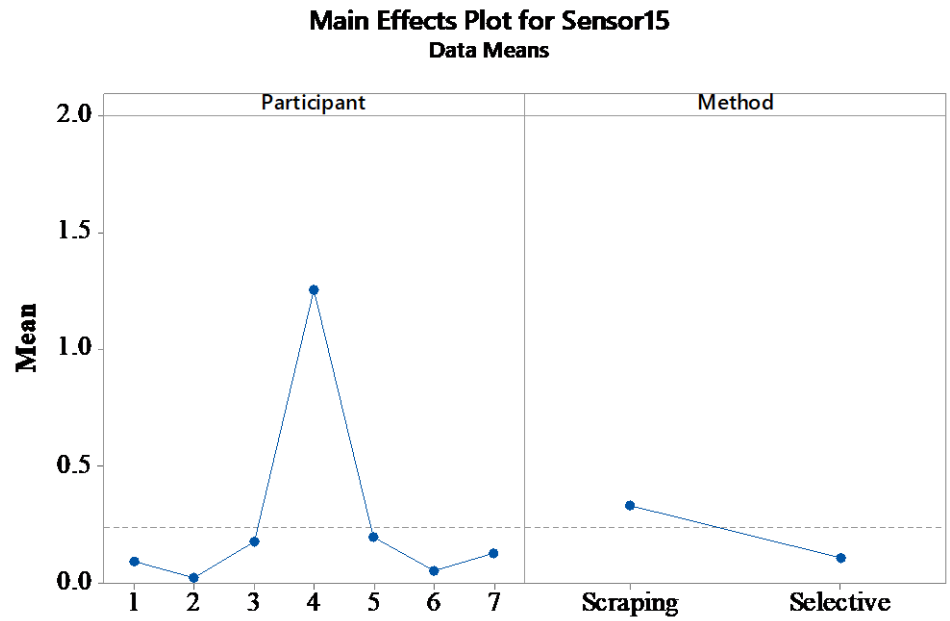


Figure E.39 Main Effect Plot for sensor 15 between participant and method variable.

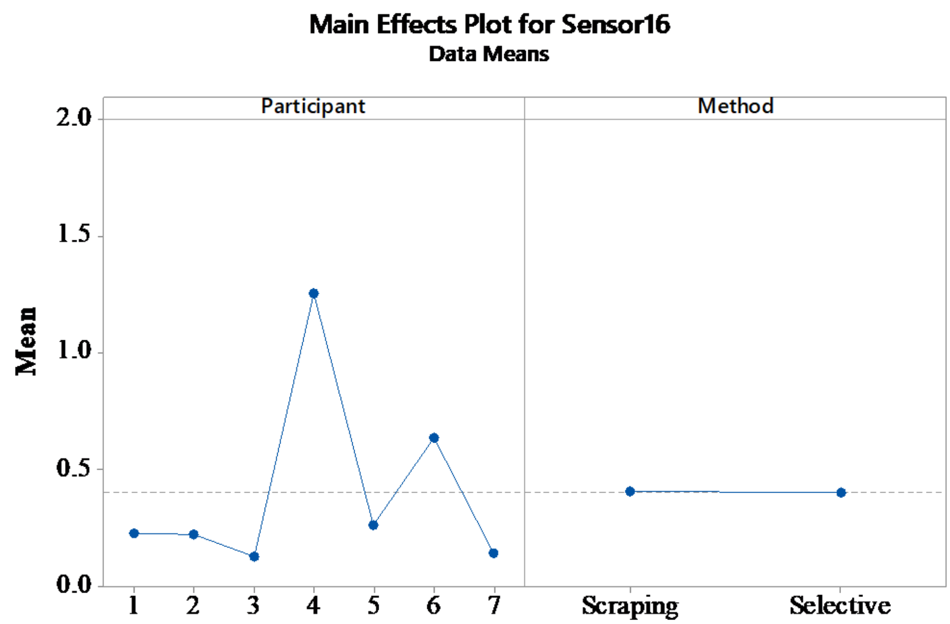


Figure E.40 Main Effect Plot for sensor 16 between participant and method variable.

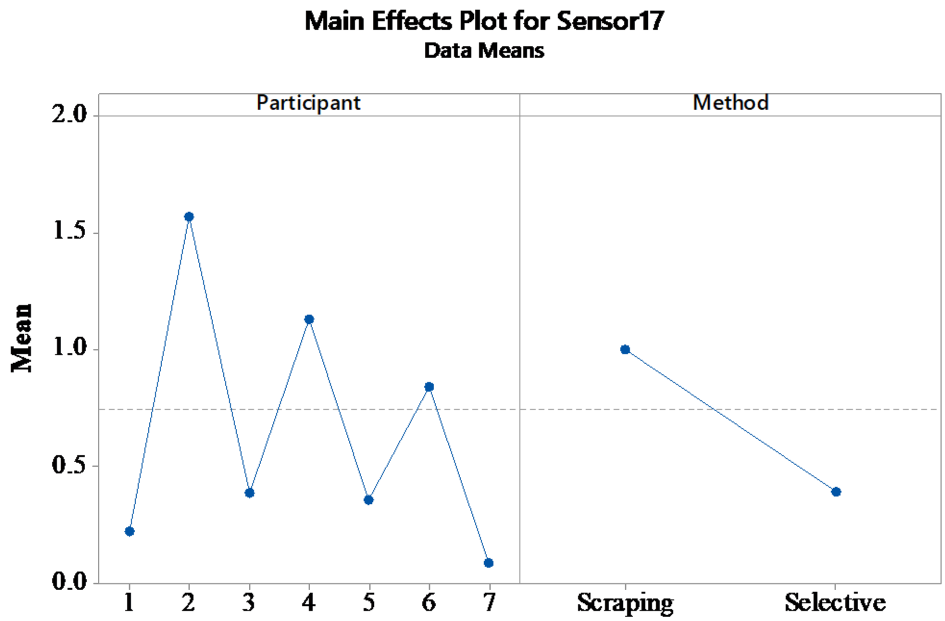


Figure E.41 Main Effect Plot for sensor 17 between participant and method variable.

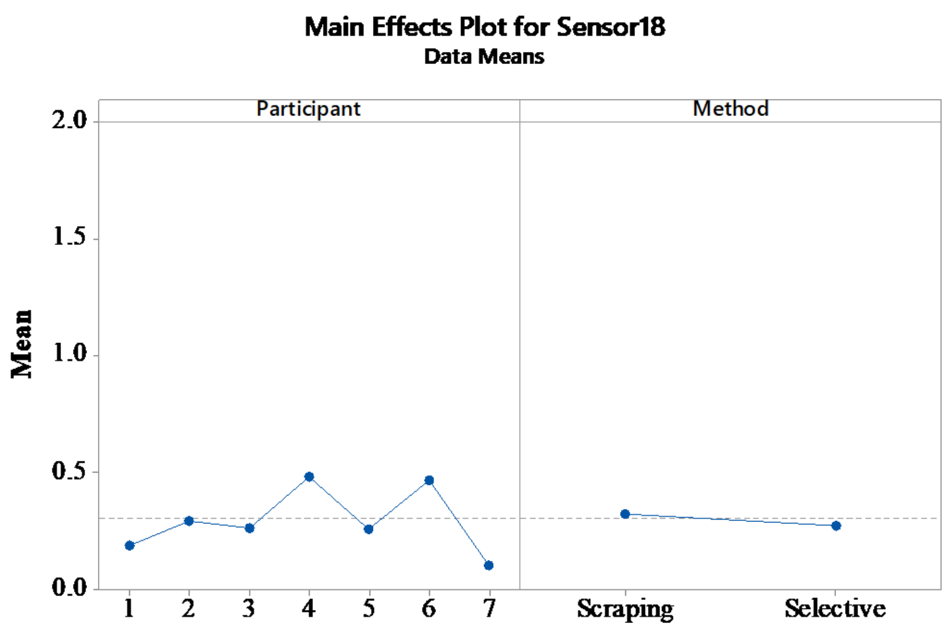


Figure E.42 Main Effect Plot for sensor 18 between participant and method variable.

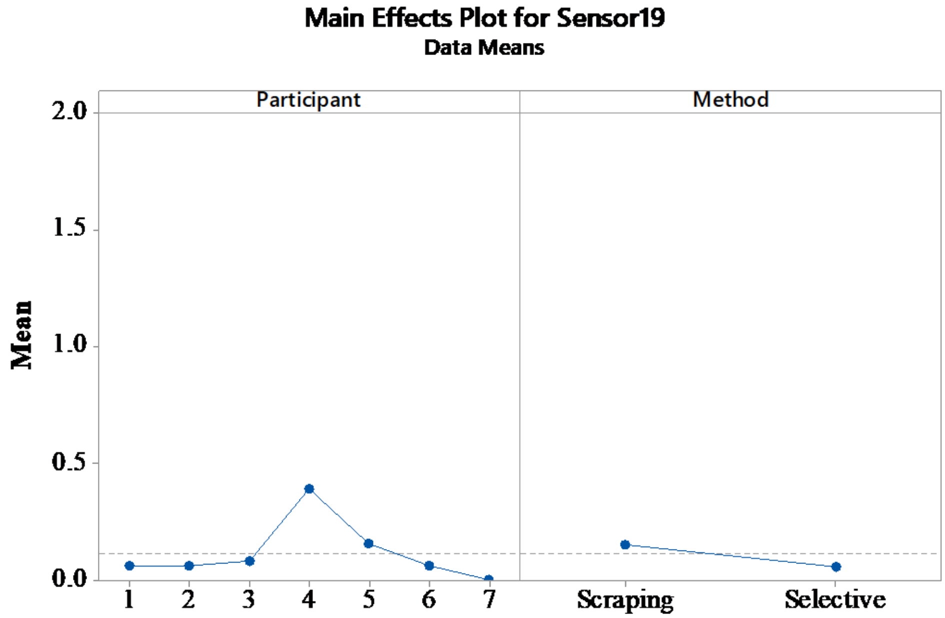


Figure E.43 Main Effect Plot for sensor 19 between participant and method variable.

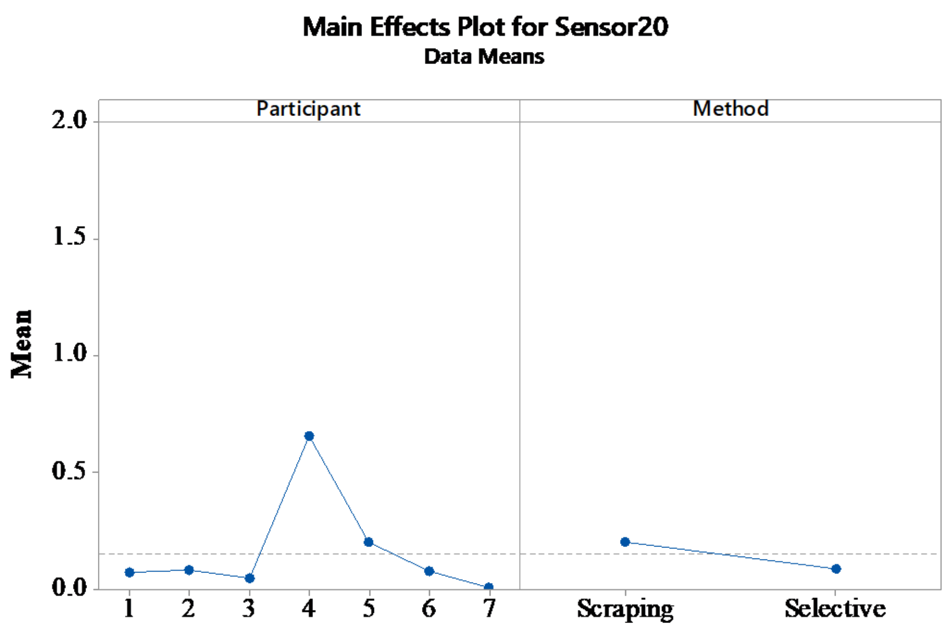


Figure E.44 Main Effect Plot for sensor 20 between participant and method variable.

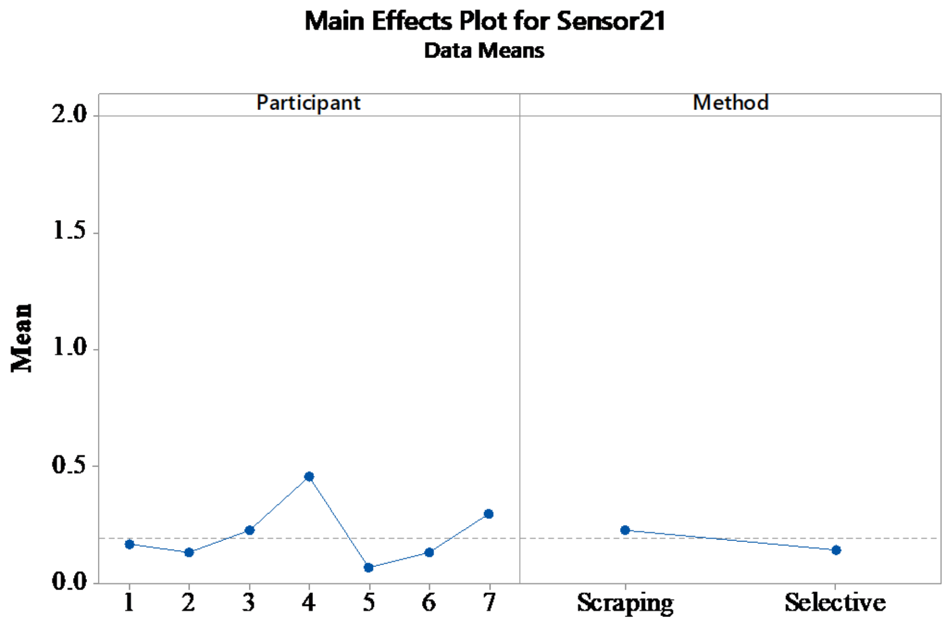


Figure E.45 Main Effect Plot for sensor 21 between participant and method variable.

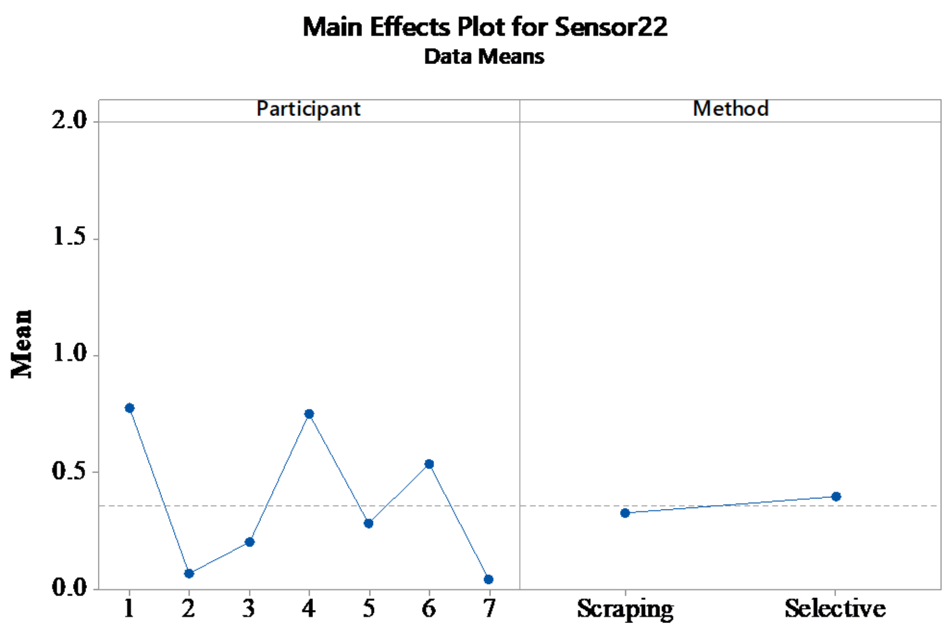


Figure E.46 Main Effect Plot for sensor 22 between participant and method variable.

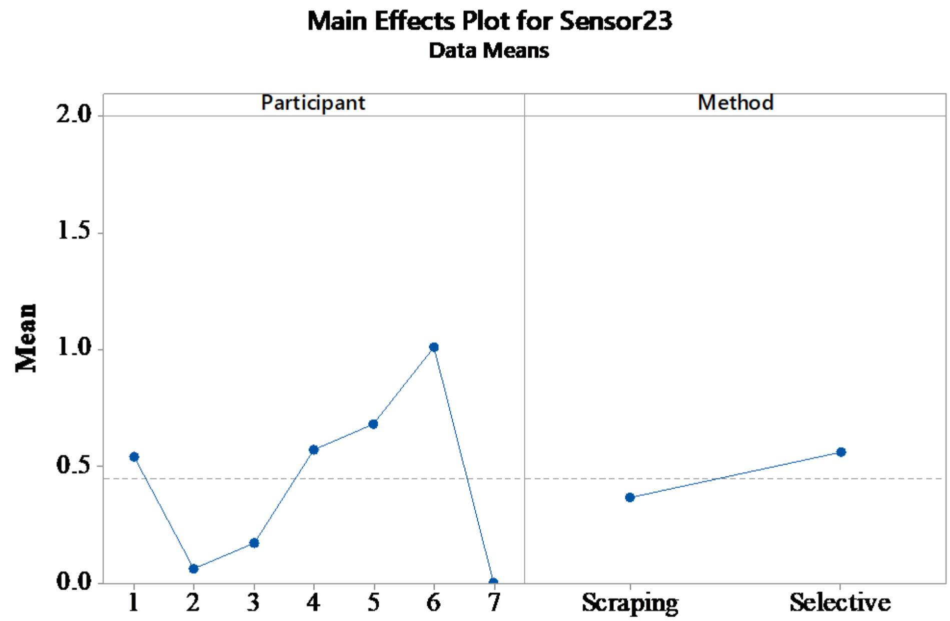


Figure E.47 Main Effect Plot for sensor 23 between participant and method variable.

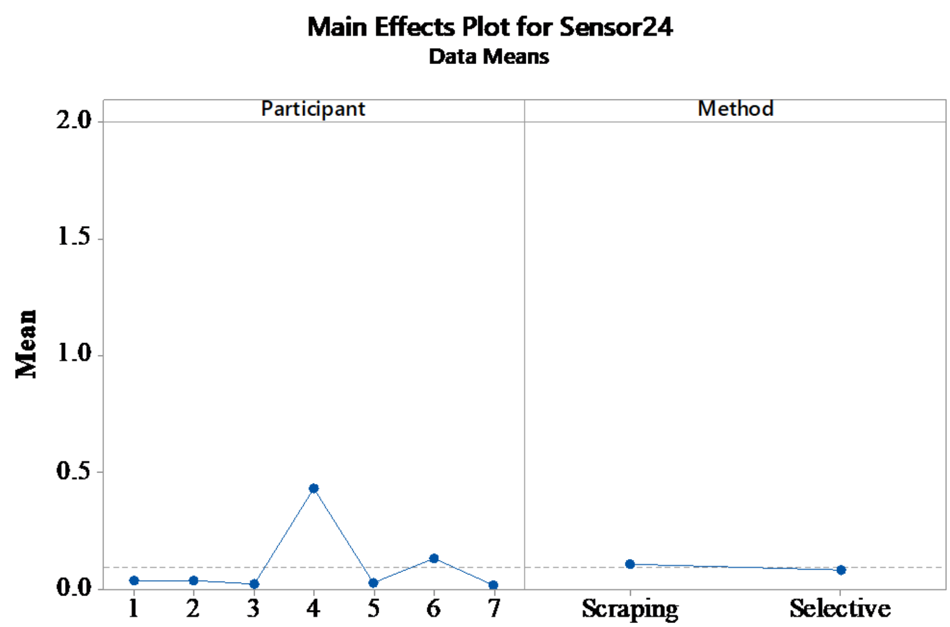


Figure E.48 Main Effect Plot for sensor 24 between participant and method variable.

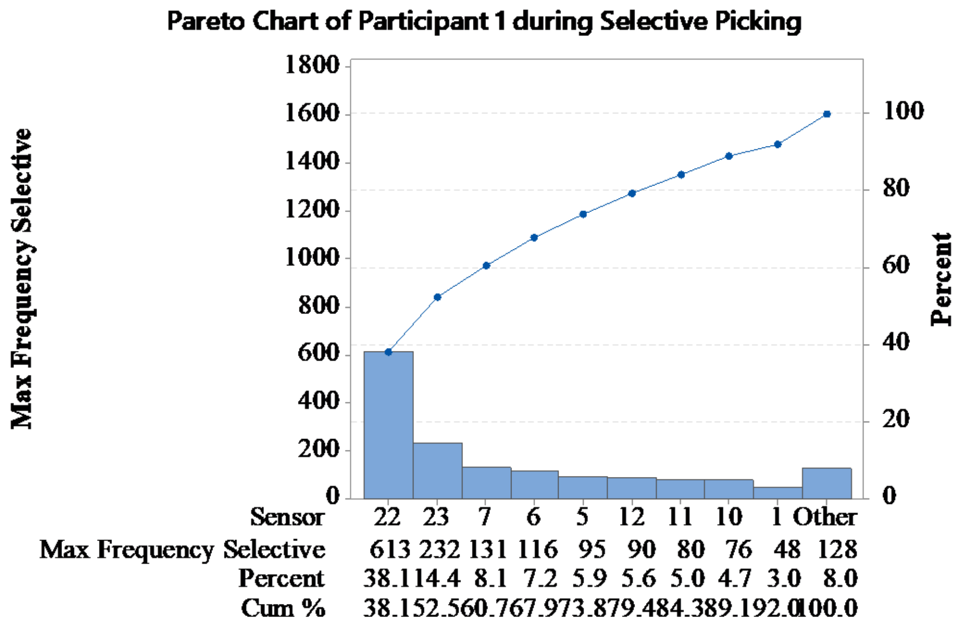


Figure E.49 Pareto of sensors for participant 1 for selective method.

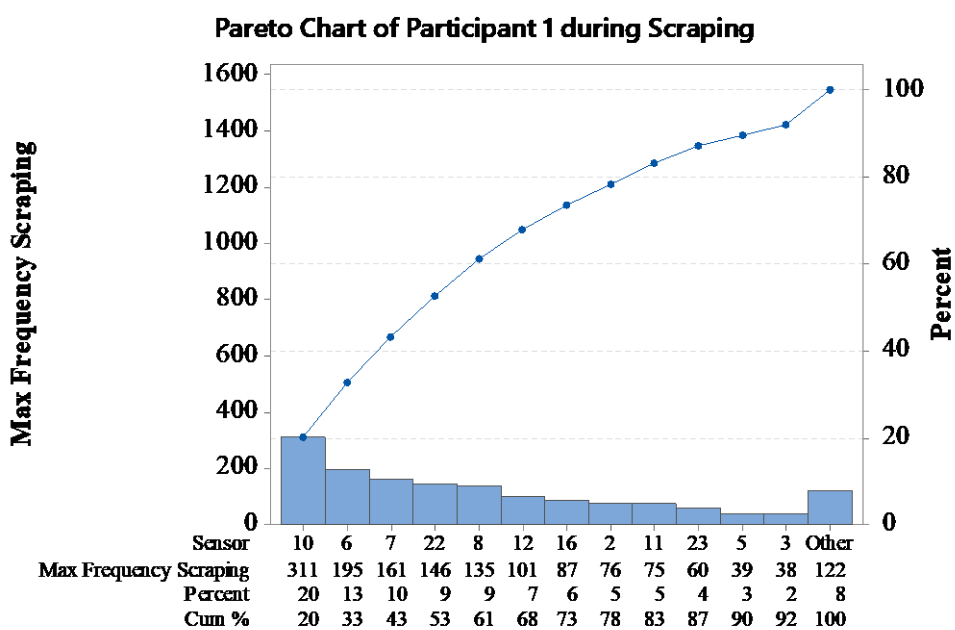


Figure E.50 Pareto of sensors for participant 1 for scraping method.

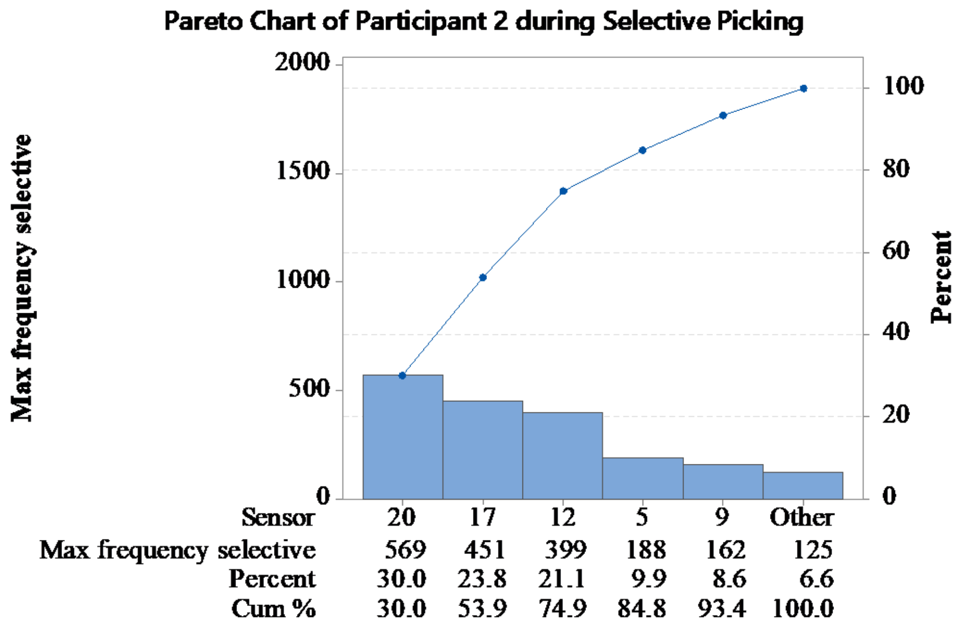


Figure E.51 Pareto of sensors for participant 2 for selective method.

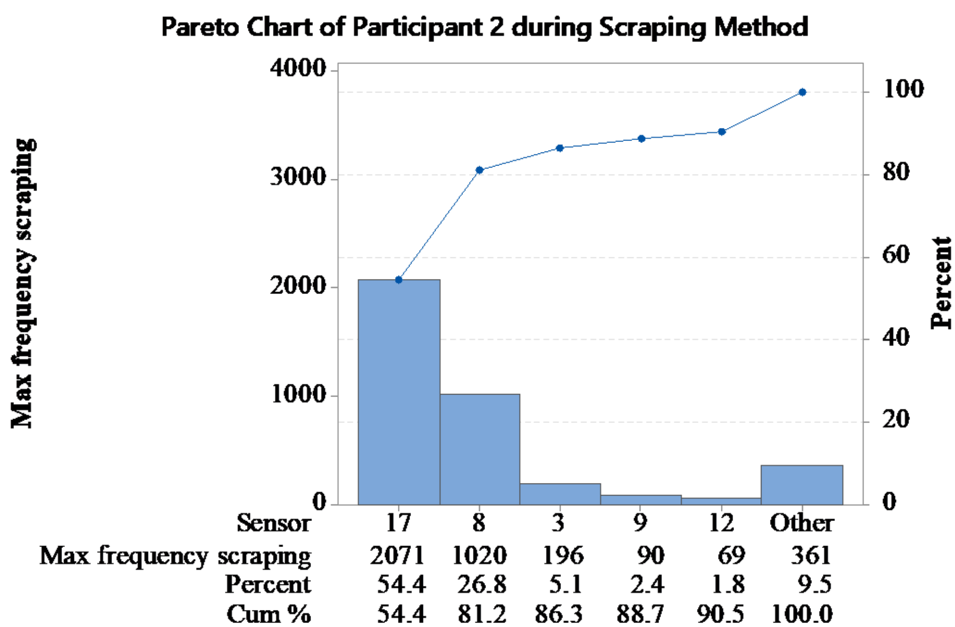


Figure E.52 Pareto of sensors for participant 2 for scraping method.

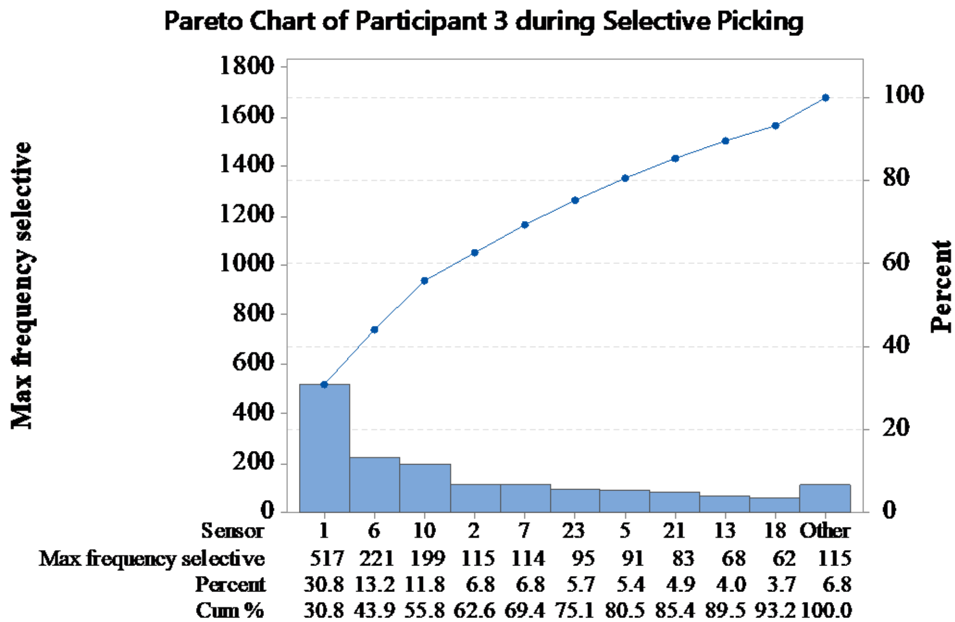


Figure E.53 Pareto of sensors for participant 3 for selective method.

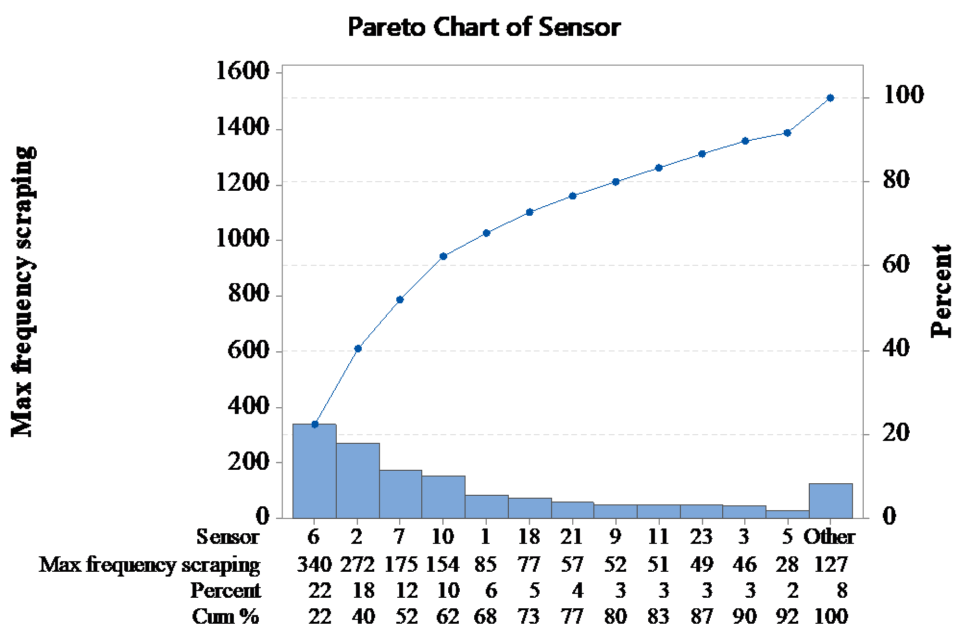
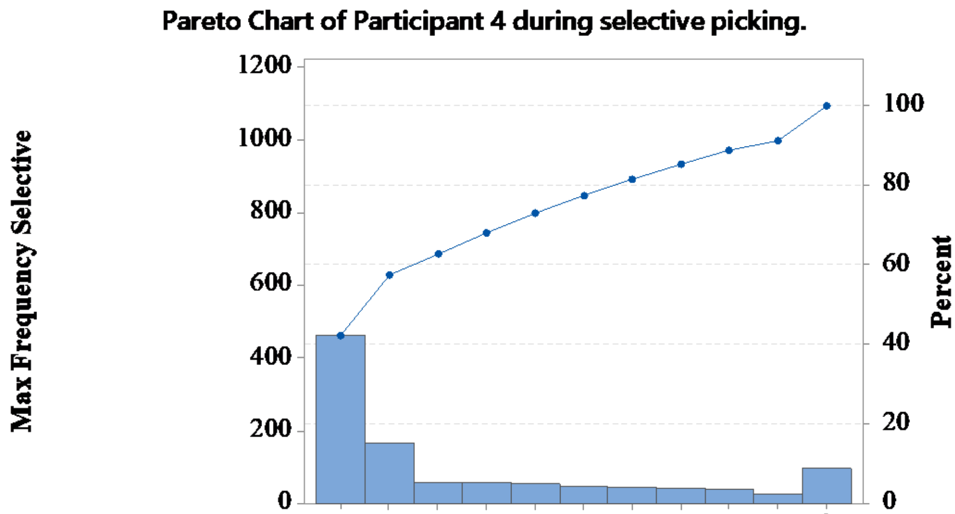
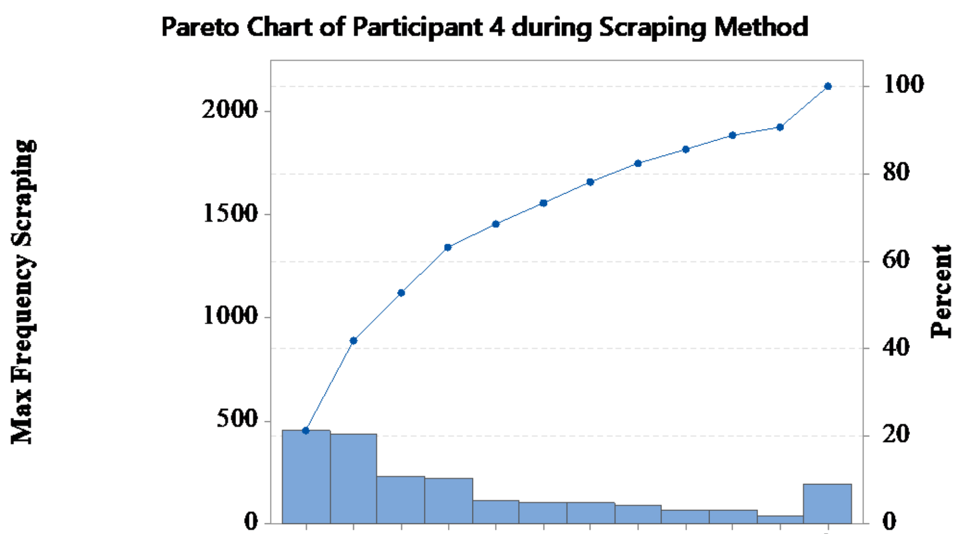


Figure E.54 Pareto of sensors for participant 3 for scraping method.



Sensor	2	10	12	16	8	4	7	1	11	5	Other
Max Frequency Selective	461	166	59	58	54	48	46	42	38	26	97
Percent	42.1	15.2	5.4	5.3	4.9	4.4	4.2	3.8	3.5	2.4	8.9
Cum %	42.1	57.3	62.6	67.9	72.9	77.3	81.5	85.3	88.8	91.1	100.0

Figure E.55 Pareto of sensors for participant 4 for selective method.



Sensor	8	10	7	12	2	11	5	15	1	16	17	Other
Max Frequency Scraping	456	434	232	222	114	101	100	89	70	68	41	195
Percent	21.5	20.5	10.9	10.5	5.4	4.8	4.7	4.2	3.3	3.2	1.9	9.2
Cum %	21.5	41.9	52.9	63.3	68.7	73.5	78.2	82.4	85.7	88.9	90.8	100.0

Figure E.56 Pareto of sensors for participant 4 for scraping method.

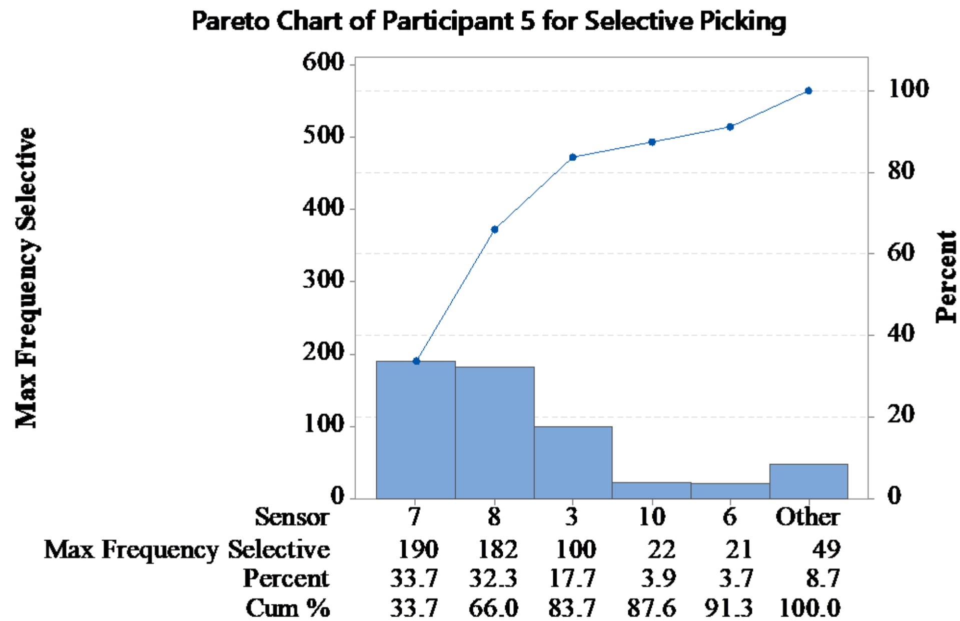


Figure E.57 Pareto of sensors for participant 5 for selective method.

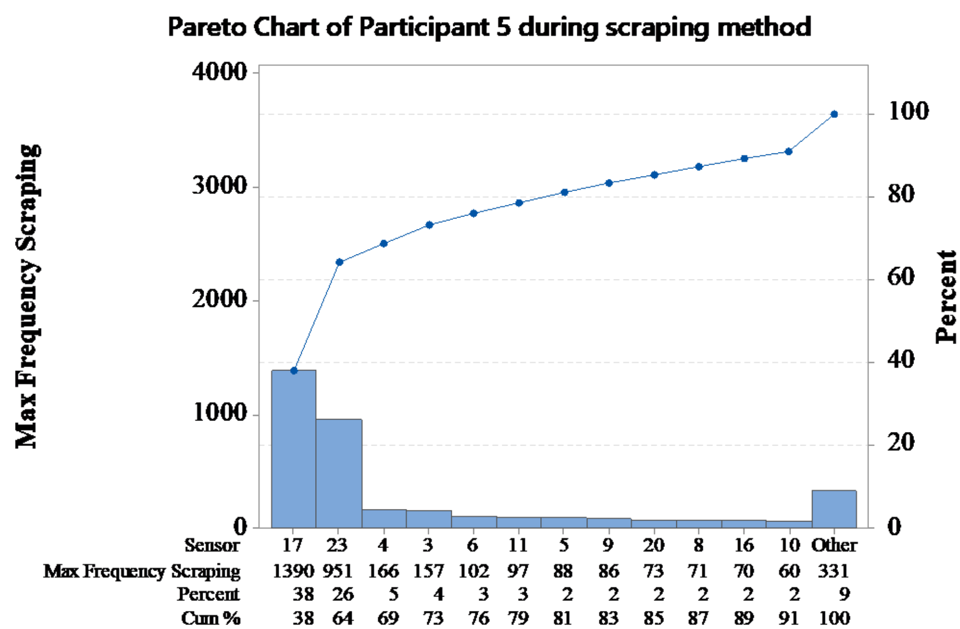


Figure E.58 Pareto of sensors for participant 5 for scraping method.

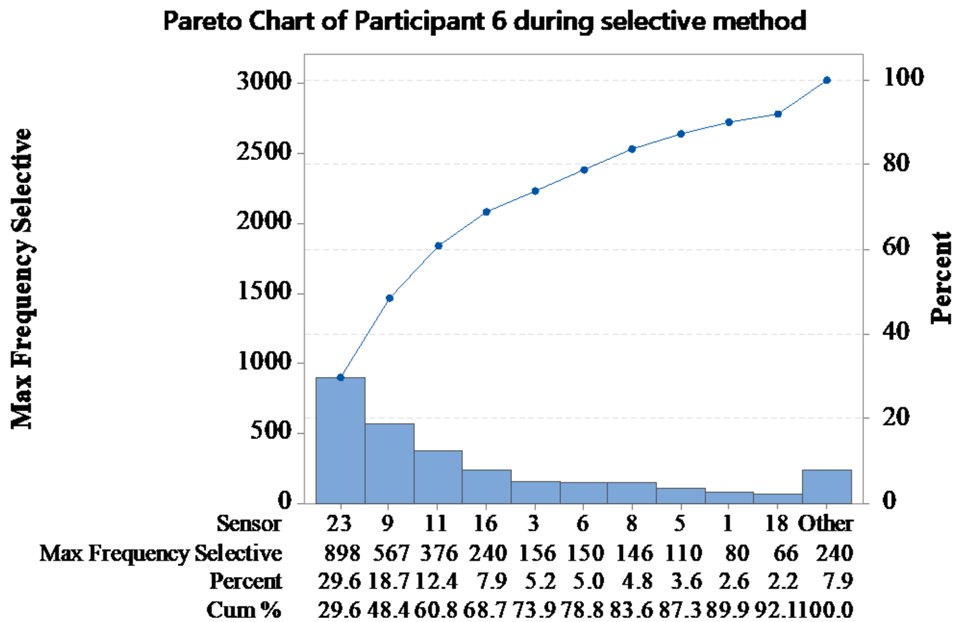


Figure E.59 Pareto of sensors for participant 6 for selective method.

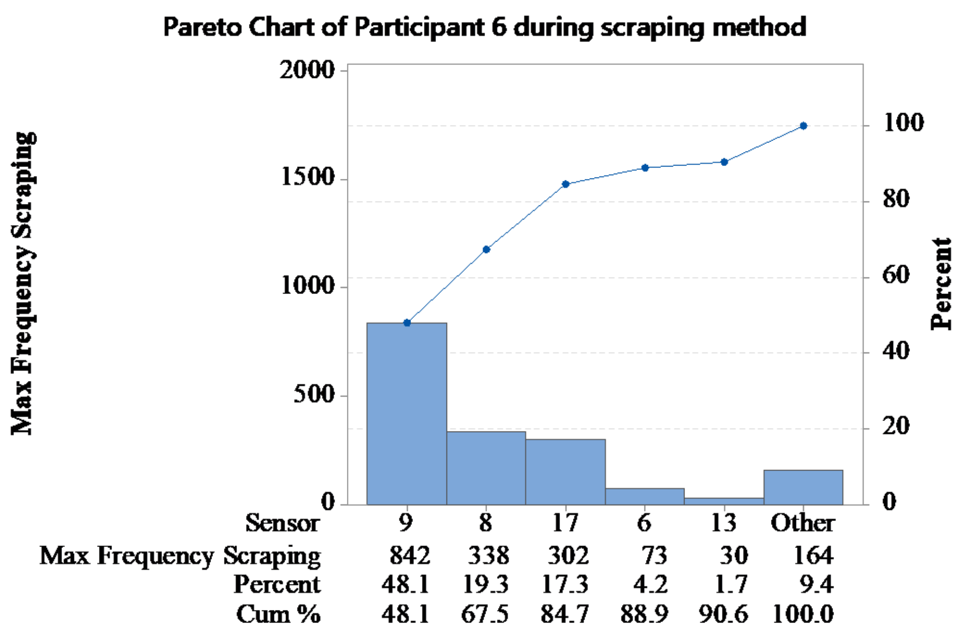


Figure E.60 Pareto of sensors for participant 6 for scraping method.

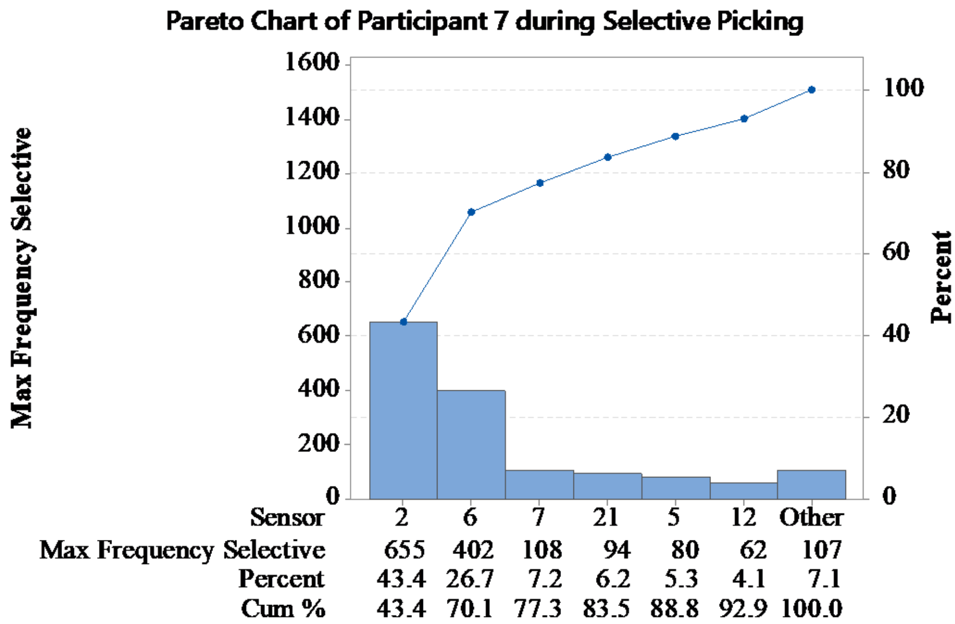


Figure E.61 Pareto of sensors for participant 7 for selective method.

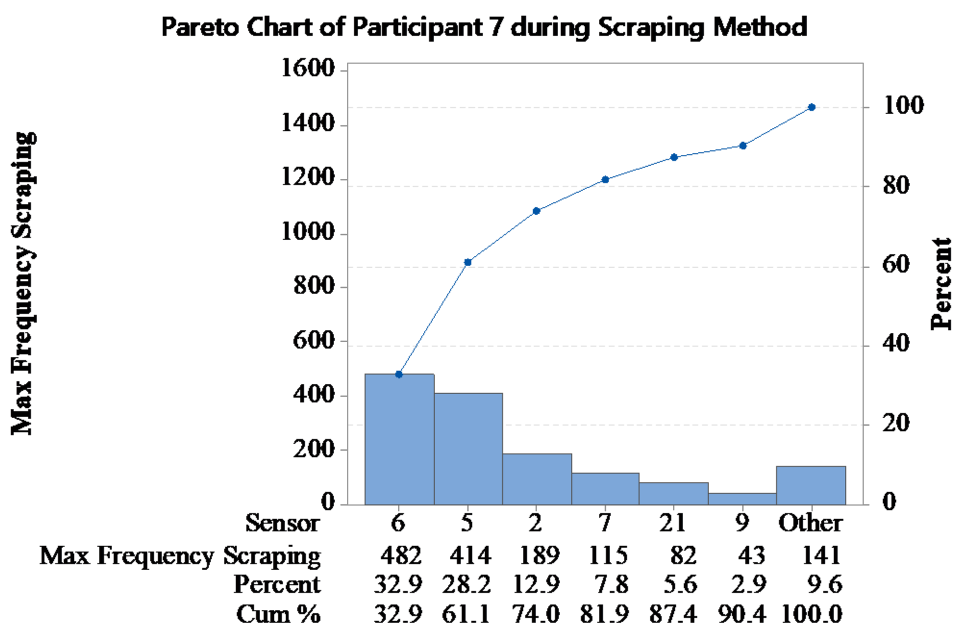


Figure E.62 Pareto of sensors for participant 7 for selective method.

Table E.49 Pareto Analysis of significant sensors per participant for the selective method.

Pareto results per person for selective method													
Sensor	**1**	**Sensor**	**2**	**Sensor**	**3**	**Sensor**	**4**	**Sensor**	**5**	**Sensor**	**6**	**Sensor**	**7**
22	613	20	569	1	517	2	461	7	190	23	898	2	655
23	232	17	451	6	221	10	166	8	182	9	567	6	402
7	131	12	399	10	199	12	59	3	100	11	376	7	108
6	116	5	188	2	115	16	58			16	240	21	94
5	95			7	114	8	54			3	156		
12	90			23	95	4	48			6	150		
11	80			5	91	7	46			8	146		

Table E.50 Pareto Analysis of significant sensors per participant for the scraping method.

Pareto results per person for scraping method													
Sensor	**1**	**Sensor**	**2**	**Sensor**	**3**	**Sensor**	**4**	**Sensor**	**5**	**Sensor**	**6**	**Sensor**	**7**
10	311	17	2071	6	340	8	456	17	1390	9	842	6	482
6	195	8	1020	2	272	10	434	23	951	8	338	5	414
7	161			7	175	7	232	4	166	17	302	2	189
22	146			10	154	12	222	3	157			7	115
8	135			1	85	2	114	6	102				
12	101			18	77	11	101	11	97				
16	87			21	57	5	100	5	88				
2	76			9	52	15	89						
11	75												

Table E.51 Resulting ANOVA and Model Summary for Selective Method (Vector 2).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	3337.2	1112.38	382.13	0
Experience	1	118.1	118.09	40.57	0
Weight	1	2572.2	2572.2	883.62	0
Age	1	6	6.02	2.07	0.151
Error	8346	24295.1	2.91		
Lack-of-Fit	2	1631.7	815.86	300.38	0
Pure Error	8344	22663.4	2.72		
Total	8349	27632.2			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
1.70616	12.08%	12.05%	11.99%		

Table E.52 Coefficients for Selective Method (Vector 2).

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	7.49	0.449	16.67	0	
Experience	0.02308	0.00362	6.37	0	10.86
Weight	0.12002	0.00404	29.73	0	1.77
Age	-0.00863	0.00601	-1.44	0.151	12.58

Regression Equation:

$$T_{PRED_{SELECTIVE_{PC2}}} = 7.490 + 0.02308\,Experience + 0.12002\,Weight - 0.00863\,Age \quad \text{(E-1)}$$

Table E.53 Resulting ANOVA and Model Summary for Selective Method (Vector 3).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	1060	353.34	269.14	0
Experience	1	280.7	280.68	213.79	0
Weight	1	51.1	51.12	38.94	0
Age	1	414.8	414.8	315.95	0
Error	8346	10957.1	1.31		
Lack-of-Fit	2	2602.5	1301.25	1299.6	0
Pure Error	8344	8354.6	1		
Total	8349	12017.1			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
1.1458	8.82%	8.79%	8.73%		

Table E.54 Coefficients for Selective Method (Vector 3).

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	19.418	0.302	64.36	0	
Experience	0.03558	0.00243	14.62	0	10.86
Weight	0.01692	0.00271	6.24	0	1.77
Age	-0.07169	0.00403	-17.77	0	12.58

Regression Equation

$$\mathrm{T}_{\mathrm{PRED}_{\mathrm{SELECTIVE}_{\mathrm{PC3}}}} = 19.418 + 0.03558\,\mathrm{Experience} + 0.01692\,\mathrm{Weight} - 0.07169\,\mathrm{Age} \quad (1\text{-}2)$$

Table E.55 Resulting ANOVA and Model Summary for Selective Method (Vector4).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	71.6	23.877	10.11	0
Experience	1	67.7	67.68	28.66	0
Weight	1	0.1	0.145	0.06	0.805
Age	1	47.8	47.83	20.26	0
Error	8346	19706.8	2.361		
Lack-of-Fit	2	1549.6	774.785	356.05	0
Pure Error	8344	18157.2	2.176		
Total	8349	19778.4			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
1.53663	0.36%	0.33%	0.25%		

Table E.56 Coefficients for Selective Method (Vector 4).

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	8.276	0.405	20.45	0	
Experience	0.01747	0.00326	5.35	0	10.86
Weight	-0.0009	0.00364	-0.25	0.805	1.77
Age	-0.02434	0.00541	-4.5	0	12.58

Regression Equation

$$T_{PRED_{SELECTIVE_{PC4}}} = 8.276 + 0.01747\,Experience - 0.00090\,Weight - 0.02434\,Age \quad \text{(E-3)}$$

Table E.57 Resulting ANOVA and Model Summary for Selective Method (Vector 5).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	1507.44	502.479	639.18	0
Experience	1	540.21	540.207	687.17	0
Weight	1	13.58	13.583	17.28	0
Age	1	911.79	911.79	1159.84	0
Error	8346	6561.08	0.786		
Lack-of-Fit	2	88.45	44.227	57.01	0
Pure Error	8344	6472.63	0.776		
Total	8349	8068.52			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.886643	18.68%	18.65%	18.59%		

Table E.58 Coefficients for Selective Method (Vector 5).

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	22.065	0.233	94.51	0	
Experience	0.04936	0.00188	26.21	0	10.86
Weight	-0.00872	0.0021	-4.16	0	1.77
Age	-0.10628	0.00312	-34.06	0	12.58

Regression Equation

$$T_{PRED_{SELECTIVE_{PC5}}} = 22.065 + 0.04936\,Experience - 0.00872\,Weight - 0.10628\,Age \quad (1\text{-}4)$$

Table E.59 Resulting ANOVA and Model Summary for Selective Method (Vector 6).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	2175	724.99	491.71	0
Experience	1	1303.7	1303.66	884.19	0
Weight	1	98.7	98.73	66.96	0
Age	1	677.6	677.57	459.55	0
Error	8346	12305.5	1.47		
Lack-of-Fit	2	64.7	32.34	22.04	0
Pure Error	8344	12240.9	1.47		
Total	8349	14480.5			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
1.21426	15.02%	14.99%	14.93%		

Table E.60 Coefficients for Selective Method (Vector 6).

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	22.457	0.32	70.24	0	
Experience	-0.07667	0.00258	-29.74	0	10.86
Weight	0.02351	0.00287	8.18	0	1.77
Age	0.09162	0.00427	21.44	0	12.58

Regression Equation

$$T_{PRED_{SELECTIVE_{PC6}}} = 22.457 - 0.07667\,Experience + 0.02351\,Weight + 0.09162\,Age \quad \text{(E-5)}$$

Table E.61 Resulting ANOVA and Model Summary for Selective Method (Vector 7).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	109.2	36.399	41.03	0
Experience	1	0	0	0	0.995
Weight	1	28.52	28.516	32.14	0
Age	1	1.51	1.512	1.7	0.192
Error	8346	7403.85	0.887		
Lack-of-Fit	2	478.72	239.361	288.4	0
Pure Error	8344	6925.13	0.83		
Total	8349	7513.05			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.941867	1.45%	1.42%	1.34%		

Table E.62 Coefficients for Selective Method (Vector 7).

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	18.222	0.248	73.47	0	
Experience	-0.00001	0.002	-0.01	0.995	10.86
Weight	-0.01264	0.00223	-5.67	0	1.77
Age	0.00433	0.00332	1.31	0.192	12.58

Regression Equation

$$T_{PRED_{SELECTIVE_{PC7}}}^{Shoulder\ Discomfort} = 18.222 - 0.00001\,Experience - 0.01264\,Weight + 0.00433\,Age \quad \text{(E-6)}$$

Table E.63 Resulting ANOVA and Model Summary for Scraping Method (Vector 2).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	4181	1393.63	291.6	0
Age	1	2719	2718.69	568.85	0
Weight	1	2974	2973.76	622.22	0
Experience	1	1115	1115.44	233.39	0
Error	14092	67349	4.78		
Lack-of-Fit	2	4570	2284.82	512.8	0
Pure Error	14090	62780	4.46		
Total	14095	71530			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
2.18615	5.84%	5.82%	5.78%		

Table E.64 Coefficients for Scraping Method (Vector 2).

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	30.552	0.484	63.17	0	
Age	-0.15791	0.00662	-23.85	0	17.3
Weight	-0.10628	0.00426	-24.94	0	2.99
Experience	0.06285	0.00411	15.28	0	14.84

Regression Equation:

$$T_{pred_{scraping_{PC2}}} = 30.552 - 0.15791\,Age - 0.10628\,Weight + 0.06285\,Experience \quad \text{(E-7)}$$

Table E.65 Resulting ANOVA and Model Summary for Scraping Method (Vector 3).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	355.6	118.53	31.24	0
Age	1	218	218.023	57.46	0
Weight	1	258.7	258.704	68.18	0
Experience	1	111.3	111.345	29.34	0
Error	14092	53474.3	3.795		
Lack-of-Fit	2	1983.1	991.574	271.33	0
Pure Error	14090	51491.1	3.654		
Total	14095	53829.9			

S	R-sq	R-sq(adj)	R-sq(pred)
1.94799	0.66%	0.64%	0.59%

Table E.66 Coefficients for Scraping Method (Vector 3).

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	35.585	0.431	82.57	0	
Age	-0.04472	0.0059	-7.58	0	17.3
Weight	-0.03135	0.0038	-8.26	0	2.99
Experience	0.01986	0.00367	5.42	0	14.84

Regression Equation

$$T_{pred_{scraping_{PC3}}} = 35.585 - 0.04472\,Age - 0.03135\,Weight + 0.01986\,Experience \quad \text{(E-8)}$$

Table E.67 Resulting ANOVA and Model Summary for Scraping Method (Vector 4).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	1545.9	515.29	428.59	0
Age	1	234.4	234.45	195	0
Weight	1	3.8	3.79	3.15	0.076
Experience	1	56.3	56.28	46.81	0
Error	14092	16942.9	1.2		
Lack-of-Fit	2	3727.5	1863.73	1987.07	0
Pure Error	14090	13215.5	0.94		
Total	14095	18488.8			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
1.0965	8.36%	8.34%	8.30%		

Table E.68 Coefficients for Scraping Method (Vector 4).

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	15.72	0.243	64.8	0	
Age	0.04637	0.00332	13.96	0	17.3
Weight	-0.00379	0.00214	-1.78	0.076	2.99
Experience	-0.01412	0.00206	-6.84	0	14.84

Regression Equation

$$T_{pred_{scraping_{PC4}}} = 15.720 + 0.04637\,Age - 0.00379\,Weight - 0.01412\,Experience \quad \text{(E-9)}$$

Table E.69 Resulting ANOVA and Model Summary for Scraping Method (Vector 5).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	1697.1	565.7	355.5	0
Age	1	1151.9	1151.89	723.88	0
Weight	1	34.1	34.07	21.41	0
Experience	1	1526.7	1526.68	959.4	0
Error	14092	22424.4	1.59		
Lack-of-Fit	2	387.7	193.85	123.95	0
Pure Error	14090	22036.7	1.56		
Total	14095	24121.4			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
1.26146	7.04%	7.02%	6.97%		

Table E.70 Coefficients for Scraping Method (Vector 5).

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	13.845	0.279	49.61	0	
Age	0.10279	0.00382	26.9	0	17.3
Weight	0.01138	0.00246	4.63	0	2.99
Experience	-0.07353	0.00237	-30.97	0	14.84

Regression Equation

$$T_{pred_{scraping_{PC5}}} = 13.845 + 0.10279\,Age + 0.01138\,Weight - 0.07353\,Experience \quad \text{(E\_10)}$$

Table E.71 Resulting Analysis of Variance and Model Summary for Scraping Method (Vector 6).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	1846	615.317	692.93	0
Age	1	0.1	0.109	0.12	0.727
Weight	1	0.6	0.571	0.64	0.422
Experience	1	122.6	122.581	138.04	0
Error	14092	12513.6	0.888		
Lack-of-Fit	2	685.5	342.751	408.3	0
Pure Error	14090	11828.1	0.839		
Total	14095	14359.5			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
0.942334	12.86%	12.84%	12.80%		

Table E.72 Coefficients for Scraping Method (Vector 6).

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	9.132	0.208	43.8	0	
Age	0.001	0.00285	0.35	0.727	17.3
Weight	0.00147	0.00184	0.8	0.422	2.99
Experience	0.02083	0.00177	11.75	0	14.84

Regression Equation:

$$T_{pred_{scraping_{PC6}}} = 9.132 + 0.00100\,Age + 0.00147\,Weight + 0.02083\,Experience \quad \text{(E-11)}$$

Table E.73 Resulting Analysis of Variance and Model Summary for Scraping Method (Vector 7).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	1097.6	365.88	240.79	0
Age	1	596.7	596.72	392.7	0
Weight	1	878.9	878.88	578.39	0
Experience	1	197.5	197.48	129.96	0
Error	14092	21413.1	1.52		
Lack-of-Fit	2	2754.1	1377.07	1039.87	0
Pure Error	14090	18659	1.32		
Total	14095	22510.7			
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**		
1.23269	4.88%	4.86%	4.80%		

Table E.74 Coefficients for Scraping Method (Vector 7).

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	20.61	0.273	75.57	0	
Age	-0.07398	0.00373	-19.82	0	17.3
Weight	-0.05778	0.0024	-24.05	0	2.99
Experience	0.02644	0.00232	11.4	0	14.84

Regression Equation

$$T_{pred_{scraping_{PC7}}} = 20.610 - 0.07398\,Age - 0.05778\,Weight + 0.02644\,Experience \quad \text{(E-12)}$$

APPENDIX F AVERAGE, MAXIMUM AND MINIMUM FORCE EXERTED

Table F.1 Average, maximum, and minimum forces exerted during Scraping Method. (in Newtons) (Participants 1 to 4)

	Participant 1			Participant 2			Participant 3			Participant 4		
Sensor	Avg (N)	Max (N)	Min (N)	Avg (N)	Max (N)	Min (N)	Avg (N)	Max (N)	Min (N)	Avg (N)	Max (N)	Min (N)
1	0.5335	11.2660	0.0069	0.0409	0.3930	0.0069	0.9029	11.4660	0.0069	0.6480	5.9709	0.0552
2	0.8616	9.0597	0.0069	0.0329	0.1655	0.0069	1.0857	12.5829	0.0069	1.1803	11.3212	0.0896
3	0.6355	10.0526	0.0069	0.6626	0.6626	0.6626	0.3899	6.0812	0.0069	0.7376	14.4238	0.0069
4	0.4563	6.0260	0.0069	0.0212	4.0679	0.0069	0.4068	8.0944	0.0069	0.2740	7.2533	0.0069
5	0.7339	6.2742	0.0069	0.3815	7.1843	0.0414	0.6443	7.2947	0.0069	0.9542	13.1759	0.0069
6	1.1407	11.0799	0.0069	0.4737	5.4813	0.0827	0.5385	5.6951	0.0069	1.2060	15.1271	0.1034
7	1.3457	19.7811	0.0069	0.2392	4.9849	0.0069	0.8840	16.5543	0.0069	1.3946	20.4568	0.0069
8	1.1436	20.6843	0.0069	0.7806	7.3291	0.2275	0.2682	5.6330	0.0069	1.8414	20.6843	0.0207
9	0.8759	7.6670	0.0069	0.6919	7.3222	0.1724	0.9504	9.5837	0.0069	0.6310	14.1067	0.0207
10	0.6442	14.4997	0.0069	0.0829	6.0743	0.0069	1.0004	20.6843	0.0069	1.1436	14.6514	0.0138
11	1.1423	11.5142	0.0069	0.3212	5.7089	0.0483	0.8811	20.6843	0.0069	1.1382	19.1054	0.0069
12	1.1866	17.5403	0.0069	0.6260	5.1021	0.0414	0.7747	16.3475	0.0069	1.9810	18.1677	0.0069
13	0.7382	11.2385	0.0069	0.0351	11.5487	0.0069	0.8345	7.5842	0.0069	0.0552	0.0552	0.0552
14	0.3448	7.1361	0.0069	0.3189	13.9205	0.0276	0.4226	4.9642	0.0069	0.1431	13.5620	0.0069
15	0.3602	5.0332	0.0069	0.1496	2.6752	0.0069	0.6166	14.5204	0.0069	0.8114	20.6843	0.0069
16	0.2114	6.4328	0.0069	0.0573	8.4806	0.0069	0.1877	10.9696	0.0069	0.9255	12.9415	0.0069
17	0.2839	8.0186	0.0069	1.4962	7.4877	0.3447	0.7005	8.2737	0.0069	0.8586	18.7262	0.0069
18	0.4885	6.5293	0.0069	0.0580	11.5556	0.0069	0.4362	6.5500	0.0069	0.2691	12.5829	0.0069
19	0.2130	4.7712	0.0069	0.7003	15.4925	0.0069	0.3102	4.9298	0.0069	0.3665	9.3286	0.0069
20	0.2544	2.7648	0.0069	0.1927	4.8194	0.0069	0.1294	3.2267	0.0069	0.3362	19.1054	0.0069
21	0.1659	2.6683	0.0069	0.0164	0.0621	0.0069	0.2043	5.6813	0.0069	0.3740	8.2599	0.0069
22	0.0454	0.0060	0.0000	0.1707	5.7227	0.0069	0.1155	3.6129	0.0069	0.4473	11.4246	0.0069
23	0.0004	0.0045	0.0000	0.0700	4.0265	0.0069	0.1840	3.3026	0.0069	0.6200	10.1215	0.0069
24	0.1596	0.0069	0.0069	0.2739	4.2816	0.0069	0.1395	3.2474	0.0069	0.4997	5.2331	0.0069

Table F.2 Average, maximum, and minimum forces exerted during Scraping Method. (in Newtons) (Participants 5 to 7)

	Participant 5			Participant 6			Participant 7		
Sensor	Avg (N)	Max (N)	Min (N)	Avg (N)	Max (N)	Min (N)	Avg (N)	Max (N)	Min (N)
1	0.0513	0.1517	0.0069	0.0000	0.0000	0.0000	0.4583	1.9788	0.0069
2	0.0000	0.0000	0.0000	0.0207	0.0276	0.0138	0.1447	8.1910	0.0069
3	1.0749	14.9134	0.0069	0.3250	4.1093	0.0689	0.2348	1.4548	0.0069
4	0.2198	5.7364	0.0069	0.0233	1.5306	0.0069	0.0530	1.2204	0.0069
5	0.3528	8.5771	0.0069	0.1650	4.4195	0.0689	0.7673	14.8237	0.0069
6	0.5878	6.5362	0.0069	0.3623	4.5643	0.1103	0.8789	19.6776	0.0069
7	0.6477	9.6320	0.0069	0.1938	4.6540	0.0138	0.4370	17.2369	0.0069
8	0.4387	5.2676	0.0069	0.4286	3.2543	0.1034	0.1140	3.5853	0.0069
9	0.1207	9.9216	0.0000	0.6907	6.1501	0.2413	0.1948	3.5439	0.0069
10	0.3361	7.2671	0.0069	0.0251	1.7582	0.0069	0.1589	1.7168	0.0069
11	0.9007	20.6843	0.0069	0.1030	3.2819	0.0414	0.4379	9.3355	0.0069
12	0.7571	13.0035	0.0069	0.2338	1.0204	0.0758	0.9960	9.5423	0.0069
13	0.9526	20.1810	0.0069	0.3450	5.4675	0.0069	0.3250	2.6269	0.0069
14	0.4665	8.6185	0.0069	0.2181	4.1093	0.0207	0.2603	1.6823	0.0069
15	0.1152	4.0955	0.0069	0.2093	0.9101	0.0069	0.1547	2.6890	0.0069
16	0.3549	10.3973	0.0069	0.2067	4.8815	0.0069	0.2767	3.3715	0.0069
17	0.3363	6.9706	0.0069	0.5399	2.8475	0.1999	0.1394	1.9926	0.0069
18	0.3839	11.2178	0.0069	0.2622	6.5983	0.0069	0.2263	1.9719	0.0069
19	0.3497	6.7017	0.0069	0.3235	2.3166	0.0069	0.0555	0.1655	0.0069
20	0.3096	8.0669	0.0069	0.1167	4.4126	0.0069	0.0754	0.2896	0.0069
21	0.1967	7.2050	0.0069	0.0800	5.2331	0.0069	0.5738	4.8263	0.0069
22	0.5116	7.5773	0.0069	0.1233	5.8605	0.0069	0.1298	0.6619	0.0069
23	0.3171	6.7982	0.0069	0.1840	4.9642	0.0069	0.0000	0.0000	0.0000
24	0.1869	4.6333	0.0069	0.7164	4.6540	0.0276	0.2317	0.5929	0.0276

Table F.3 Average, maximum and minimum forces exerted during Selective Picking. (in Newtons) (participants 1 to 4)

	Participant 1			Participant 2			Participant 3			Participant 4		
Sensor	Avg (N)	Max (N)	Min (N)	Avg (N)	Max (N)	Min (N)	Avg (N)	Max (N)	Min (N)	Avg (N)	Max (N)	Min (N)
1	1.0108	13.4172	0.0069	0.0752	0.5033	0.0069	0.9657	1.8901	0.2357	0.8985	15.6718	0.0069
2	0.8616	7.3774	0.0069	0.0161	0.0345	0.0069	0.9618	2.0825	0.0854	1.4727	20.6843	0.0069
3	0.4150	2.8337	0.0069	1.3839	4.5023	0.5447	0.2604	0.5527	0.0714	0.5230	7.1016	0.0069
4	0.1927	2.6062	0.0069	0.0464	0.0827	0.0138	0.0447	0.0765	0.0176	0.3051	20.6843	0.0069
5	0.8783	15.4374	0.0069	0.0274	10.0732	0.0069	0.6767	1.4357	0.1297	1.2677	7.5222	0.0069
6	0.9321	9.2666	0.0069	0.9648	4.0955	0.2689	0.3570	1.3594	0.2212	0.6186	9.3148	0.0069
7	0.7012	13.1966	0.0069	0.1554	4.8608	0.0069	0.7000	1.3377	0.1616	0.7230	7.0094	0.0069
8	0.4073	6.8051	0.0069	1.2388	17.8436	0.3723	0.2525	0.4622	0.0437	0.9444	9.9009	0.0069
9	0.6011	5.1642	0.0069	1.6631	20.6843	0.1931	0.5432	0.9392	0.1316	1.0220	8.2875	0.0069
10	0.2291	6.7431	0.0069	0.0193	11.3350	0.0069	0.2512	0.9328	0.0566	1.1801	14.5135	0.0069
11	0.3154	3.9300	0.0069	0.4756	7.5153	0.0138	0.3182	0.6359	0.1332	1.3461	20.6843	0.0069
12	0.4097	2.2339	0.0069	0.0926	9.6802	0.0069	0.2013	0.3387	0.0576	1.3473	10.6386	0.0069
13	0.2181	3.0130	0.0069	0.0866	9.5561	0.0069	0.5735	1.0676	0.1348	0.8533	7.7842	0.0069
14	0.0900	1.8685	0.0069	0.4288	1.9030	0.3172	0.1118	0.1586	0.0069	0.3522	4.1438	0.0069
15	0.2031	3.8817	0.0069	0.1739	1.5927	0.0069	0.2433	0.5214	0.0742	0.6516	6.3087	0.0069
16	0.0614	1.2824	0.0069	0.3534	0.4619	0.2275	0.2685	0.4808	0.1586	0.8094	6.5638	0.0069
17	0.1467	1.7030	0.0069	0.1614	0.7791	0.0069	0.4538	0.7525	0.1916	0.6586	6.8672	0.0069
18	0.1227	2.6269	0.0069	0.0155	0.1931	0.0069	0.2481	0.4273	0.0676	0.6213	6.7017	0.0069
19	0.2467	2.2477	0.0069	0.0092	0.0414	0.0069	0.0995	0.3534	0.0544	0.1871	20.6843	0.0069
20	0.0689	1.1997	0.0069	0.1355	6.9982	0.0069	0.0302	0.0432	0.0162	0.2776	13.4172	0.0069
21	0.0458	1.3445	0.0069	0.0108	8.7081	0.0069	0.1033	0.2201	0.0401	0.2378	3.3440	0.0069
22	0.3819	4.2679	0.0069	0.0222	0.4068	0.0069	0.1002	0.1984	0.0493	0.5612	5.9226	0.0069
23	0.3753	3.8197	0.0069	0.0631	0.1586	0.0069	0.1060	0.2419	0.0290	0.5676	4.1575	0.0069
24	0.2304	1.8064	0.0069	0.0000	0.0000	0.0000	0.1103	0.1586	0.0621	0.4403	3.4405	0.0069

Table F.4 Average, maximum and minimum forces exerted during Selective Picking. (in Newtons) (participant 5 to 7)

	Participant 5			Participant 6			Participant 7		
Sensor	Avg (N)	Max (N)	Min (N)	Avg (N)	Max (N)	Min (N)	Avg (N)	Max (N)	Min (N)
1	0.4173	0.8343	0.0689	6.6226	20.6843	0.0069	0.5991	7.1292	0.0069
2	0.1066	0.2206	0.0138	0.0904	1.0618	0.0069	0.4335	11.5142	0.0069
3	1.2849	2.0753	0.3516	0.4638	6.9292	0.0069	0.2838	12.4037	0.0069
4	0.0545	2.0271	0.0069	0.1539	4.5092	0.0069	0.0988	3.4819	0.0069
5	0.7562	6.1639	0.2482	0.4383	20.6843	0.0207	0.7305	9.9422	0.0069
6	0.8571	2.1718	0.1931	0.5019	4.2058	0.0896	1.0160	17.4851	0.0069
7	1.5374	3.7439	0.8205	0.3569	6.3639	0.0069	0.4867	7.4808	0.0069
8	1.4852	3.1095	0.7791	0.6071	5.9571	0.1862	0.0752	1.6478	0.0069
9	0.9775	3.1164	0.3654	0.8040	4.9091	0.3172	0.2429	2.9303	0.0069
10	0.8471	7.5980	0.1999	0.2337	5.2193	0.0069	0.1340	2.0271	0.0069
11	0.9174	2.2063	0.3723	0.9003	7.6739	0.0483	0.3987	4.5850	0.0069
12	0.9947	3.4887	0.2758	0.4968	5.4951	0.0414	1.0769	17.1886	0.0069
13	0.0351	5.7985	0.0069	0.5106	5.7295	0.0069	0.2812	2.1167	0.0069
14	0.0401	1.9719	0.0069	0.2622	5.1504	0.0069	0.2855	2.7234	0.0069
15	0.1639	3.1302	0.0276	0.0984	1.8616	0.0069	0.1641	1.6685	0.0069
16	0.0565	3.0613	0.0069	0.5406	6.5638	0.0069	0.3297	3.9507	0.0069
17	0.1843	5.1297	0.0069	0.6005	3.4750	0.1034	0.0638	0.8894	0.0069
18	0.0263	0.8343	0.0069	0.4278	4.6402	0.0069	0.2056	1.0549	0.0069
19	0.0300	1.9030	0.0069	0.2054	4.7367	0.0069	0.0516	0.1172	0.0069
20	0.0330	2.4614	0.0069	0.1627	4.0955	0.0069	0.0873	0.4826	0.0138
21	0.0421	0.3447	0.0069	0.1000	1.6754	0.0069	0.5502	5.4675	0.0069
22	0.0390	1.0618	0.0069	0.6039	3.1026	0.0069	0.1363	0.8963	0.0069
23	0.0780	2.5786	0.0069	1.0852	4.4678	0.0069	0.0000	0.0000	0.0000
24	0.0919	0.5654	0.0069	0.1705	2.1443	0.0069	0.1534	0.5792	0.0069