Inducing the Learning of Ergonomics and Anthropometric Design using Motion Capture and Virtual Simulation in an Industrial Context

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Abstract: Through this paper, we present an approach that simplifies the understanding of ergonomics and anthropometric design to Mechatronics Engineering students at Tecnológico de Monterrey by presenting both the theory behind those topics and a practical approach using specialized software and hardware. The latter, carried out in an industrial context to avoid musculoskeletal diseases at work, assisted the sensitization of engineering students into designing products and workstations that would account for the needs of their users.

1 INTRODUCTION

A central and important concept in human factors is "the system", an entity that exists to carry out some purpose and is composed of humans, machines, and other elements that, in many ways, work together. The elements of a system interact to accomplish some goal which could not be produced independently by their components.

Therefore, we can consider a man-machine system as a combination of one or more human beings interacting with one or more physical components, in which certainly given inputs produce some desired outputs. In this approach of the man-machine systems is where the ergonomics was born.

Ergonomics works as a multidisciplinary subject and in order for it to be applied in a consistent and coherent way, a model or framework is required which specifies its areas of application, boundaries, and limitations (Bridger, R.S., et al 1995). We cannot get this framework to be derived from the study of anatomy, psychology, or physiology alone since these sciences are focused at the level of the human component rather than as part of the work systems.

Ergonomics studies the human component in the context of different activities. Particular emphasis is placed on the design of human-machine interfaces (HMI) to ensure increased safety and usability of equipment and the removal of harmful stressors decreasing risks.

Hence, the basic objectives that are pursued with ergonomics when analysing and treating this type of systems, are mainly related to the improvement of the person-machine interrelation and control, the environment of the workplace, and staying under the limits of action of the person, helping us to detect and correct risks of physical and/or psychological fatigue. This requires to create databases that possess enough knowledge about the limitations which are comprehensive enough for different populations.

We can think about ergonomics as a research and practice field regarding the projects of a conception of jobs and leisure, and the functional attributes of the products and services (Mondelo et al., 2001). Thus, the importance of understanding ergonomics and its relation to product design, by both designers and engineers, is significant in order to avoid tasks that may lead to injuries.

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There are several risk factors to be mindful at workstations either office or factories where we can find systems of human-machine interaction for long hours of work shifts. This way, taking no importance on ergonomics can derive to several problems and injuries on users, such as Musculoskeletal disorders (MSD) which are injuries or disorders of the muscles, nerves, tendons, joints, cartilage, and spinal discs. Work-related musculoskeletal disorders (WMSD) are conditions in which the work environment and performance of work contribute significantly to that condition.

Just in Mexico, WMSD has been reported as the third cause for years lived in disability, and the seventeenth cause of years of life lost (Clark et al., 2018). Additionally, good ergonomics can improve safety and comfort, and so they can lead to increasing the productivity of workers (Zagloel et al., 2015).

Ergonomics aims to ensure that human needs for safe and efficient working are met in the design of work systems, this ability of people to do their jobs is influenced by both physical design and job content. Design students usually underestimate the needs of good ergonomics and anthropometric design until they create their first physical prototype, as they care more about aesthetics and functionality (Dias et al., 2015). Engineering students are even less likely to think about these topics. Through this paper, we present an innovative way to present Ergonomics and Anthropometric Design to engineering students, with a theoretical approach supported by a practical approach in an industrial context and involving technologies.

This article is organized as follows: Section 2 presents a background in the study of ergonomics and anthropometric design as it is taught to Industrial Designers at the faculty and some proposals from different authors that involve the use of technology. Section 3 introduces the context of teaching these topics for Mechatronic Engineers and details the learning experience that was designed. Section 4 presents the validation of this instructional design learning strategy and Section 5 opens the conversation for future work.

2 BACKGROUND

Human has been aware of the relation between their body and the objects around them since prehistoric times. For example, the length of the first arrows was designed for maximum reach in the drawing of the bow. Egyptians built chairs, ventilated beds and seaworthy boats just by referencing it multiple times to the cubit (i.e. elbow to the tip of the middle finger).

The arrival of the machines during the past 200 years brought an early modern period in which the operator's needs come last. The first machine designs were thought to be used by a certain population size. When operators of those specific dimensions became scarce, the concept of *human engineering* (a term coined by the United States Army) began by analyzing the workspace to accept a variable population.

Before World War II, engineers and architects had some physical guidelines based on the average man. The Department of Agriculture was in charge of taking these measurements but this was not always accurate for human engineering. It was until World War II, under the statement that machines win wars and the fact that they were becoming more complex, that the relation between human-machine acquired importance.

In Britain, the field of ergonomics was born after World War II, and the name was invented by Murrell in 1949, despite objections that people would confuse it with economics. The emphasis was on equipment and workspace design and the relevant subjects were held to be anatomy, physiology, industrial medicine, design, architecture, and illumination engineering. In the United States, a similar discipline emerged, known as *human factors*, but its scientific roots were grounded in psychology (Mondelo et al., 2001).

The word "anthropometry" comes from the Greek words *Anthropos* (man) and *metron* (measure). Anthropometric data is used in ergonomics to specify the physical dimensions of workspaces, equipment, furniture, and clothing so as to "fit the task to the man" (Grandjean, 1973) and to avoid physical mismatches between the dimensions of equipment and products, and the corresponding user dimensions.

According to Pheasant (1996), anthropometry historical antecedents date back to the Renaissance. However is well known that this discipline emerged during the nineteenth century and, among other aspects, focuses on physical differences between people of different ethnics origins (Tilley & Henry Dreyfuss Associates, 2002). In order to perform such comparisons, it was essential to develop measurement techniques to obtain data from individuals, and statistical methods to process that data. The data can be used only to assess individuals from the same population from which they were sampled, and can be categorized in different ways:

Structural anthropometric data contains all measurements of the bodily dimensions of subject in static positions. Measurements are made from one clearly identifiable anatomical landmark to another or to a fixed point in space (e.g. the height of the knuckles above the floor). Many structural variables are important in the design of vehicles, products, workspaces, and clothing (Bridger, 1995). Any person involved in a process design should be advised to study the anthropometry tables and differences in body proportion between different groups (e.g. there is an approximately 10 cm height difference between the U.S. and Japanese males in the standing position which might imply differences in product design).

The second type of anthropometric data is the one collected to describe the movement of a body part with respect to a fixed reference point. For example, to account for the maximum forward reaches of standing subjects, the area swept out by the movement of the leg can be used to describe *workspace envelopes* (i.e. zones of easy or maximum reach around an operator). The size of the workspace envelope increases with the number of unconstrained joints (Bridger, R.S., et al. 1995).

Ergonomic evaluations in workplaces can help identify the levels of risk that are within the permitted range, in order to increase efficiency both for operators and owners of the business. Modern ergonomics contributes to the evaluation of work systems and products with multidisciplinary teams that include them at different stages of design and manufacturing. Therefore, it is highly important to practice and develop these abilities in students, whether engineers or designers.

At Universities, ergonomics evaluation has for the main purpose to detect the risk levels for the operators that are present in a workplace and to consider health problems due to bad ergonomics or by the lack of anthropometric data. As expressed by Davies and Bingham, 2015, design and engineering students and lecturers have recognized the importance of applying ergonomic principles within the design process but the amount and of this teaching varies even within the same university due to time constraints and the ability of students to assimilate information.

As presented in Jellema et al. (2019), the use of software can raise awareness in students about the benefits of 3D anthropometry in Ergonomic Product Design. Moreover, the use of 3D human models with software such as NX (Baier et al., 2014) and its human modelling tool or DhaibaWorks (Endo et al., 2014) might improve design decisions to optimize specific purposes. Tecnomatix Jack, for example, is used in a case study of hospital bed design using OWAS and RULA posture analysis (Gunther and Quintero-Durán, 2015) and along with a Kinect to identify correct postures in a supermarket (Colombo et al., 2013). The latter was the main inspiration for the Instructional Design strategy presented here, which enhances the learning experience of the ergonomics and anthropometrics topics for engineering students.

The strategy was carried out as part of an optative course, in which a motion-capture camera was used along an academic license of commercially available software to evaluate postures. The description of the activity is detailed in the following sections.

3 VIRTUAL ERGONOMICS AND ANTHROPOMETRICS

Mechatronics Engineering students at Tecnológico de Monterrey who started their major between 2007 and 2018 take two mandatory courses related to Engineering Product Design: Mechatronic Design and Mechatronics Laboratory.

In these courses, some basic concepts on Anthropometry and Ergonomics are introduced, being this the only common approach of the students to such concepts through their major:

- Introduction to ergonomics.
- Consequences of bad ergonomics.
- Visual ergonomics.
- Methods to assess posture ergonomics such as Ovako Working Analysis System (OWAS), Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA).
- International standards on ergonomics.
- Virtual tools and commercially available mechatronic sensors for ergonomics in different contexts (sports, work, driving car).
- Introduction to anthropometric design and procedure to account for the 5-95 percentiles in the design of products and workstations.
- Examples of measurements in different positions and the relation to the design parameters.
- Video of research carried out by a university to improve crash dummies for changing populations.

The approach is theoretical and limited to a 1-hour session, and students usually don't ask questions regarding this part. However, once they are requested to apply those concepts to their own product, they struggle to develop them. The main proposals of this article is to make use of a simple task that, with the help of technology, can help Mechatronic Engineering students understand better the concepts of Ergonomics and Anthropometrics.

3.1 Advanced Industrial Automation

The bachelor in mechatronics engineering has specialized topics in the last semesters, such as the Advanced Industrial Automation (AIA) course that is taught on a yearly basis. AIA requires that students have completed at least one basic automation course, two control engineering courses, and two intermediate courses on industrial networks and Programmable Logic Controllers (PLC). Due to the speciality of the course and the infrastructure capacity of the laboratory, only a maximum of fifteen students per course is accepted.

AIA course focuses on designing, evaluating, validating and optimizing production processes through the application of product lifecycle management solutions together with industrial automation technologies such as PLC, industrial networks and human-machine interfaces. The topics, oriented towards manufacturing processes and not in product design, include methodologies for process modeling, digitization and information gathering, facility design and simulation, virtual commissioning and digital twins, PLC Programming and start and stop modes guide (GEMMA), offline Robot Programming, cyber-physical systems, virtual ergonomics, and mixed reality (Villagomez et al., 2019).

3.2 A Workshop in the Context of an Optative Course

Every module of the course has practices related to one of the topics mentioned above. These activities are divided in a brief presentation of the theoretical concepts, exercises solved by students through the guidance of the lecturer, and an online training course given at learning advantage platform by Siemens Digital Industries Software (Siemens DIS, 2019).

At the end of each module, a comprehensive practice is assigned to the students, allowing them to practice the knowledge acquired during the module. Short exams are applied to evaluate the quality of their learning. Finally, a high percentage of the final grade is assessed with a final project. The project includes all of the topics of the course and requires the application of the knowledge and skills that have been developed since the first semester of their major.

The final project is divided into several subprojects: PLC programming of a modular assembly line, the deployment of an algorithm to diagnose communication failures between PLC's, the creation of a digital twin of the assembly line, the connection of the digital twin with the PLC's program, and the virtual ergonomics analysis which will be detailed in the next subsections.

3.3 Tecnomatix Portfolio

Students learn several software tools to create digital twins of automated processes, including the modeling of workstations and workers' interactions. All the software used in the course was developed by Siemens Digital Industries Software.

Siemens DIS includes around 250 software solutions to support the development of products and process life cycle. In the case of the project, two main suites were used: NX, a platform that allows performing computer-aided design, engineering and manufacturing; and the Tecnomatix portfolio, for digital manufacturing.

Within the Tecnomatix portfolio there is software that helps us to model and simulate industrial plants through discrete event simulation (Plant Simulation), the design of bill of process (Process Designer), robots' offline programming (RobotXpert), design of virtual environments and virtual commissioning (Process Simulate), and for the design of operations that require operators (Jack). Some simulations and modeling examples are presented in Figure 1.

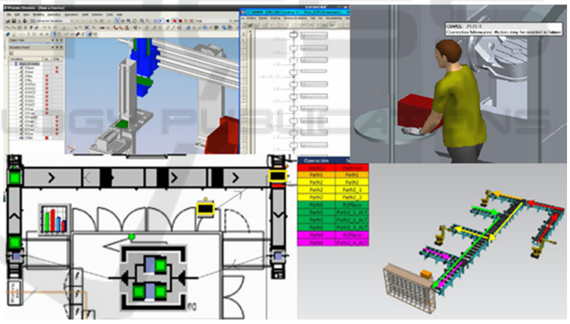

Figure 1: Example of 3D models made in NX and simulations made in Tecnomatix portfolio.

The software Jack allows creating virtual dummies (a male: Jack, and a female: Jane, depicted in Figure 2) with anthropometric characteristics of a human body. With the information of the joints of the human body, the software allows creating postures that a human would perform in the real world. Additional information from the objects or environments with which you would be interacting (size of the objects, the weight of the objects) and the activities that would be performed (pushing or pulling objects, walking, changing postures) simplify the analysis of postures at work to avoid a possible musculoskeletal injury in an individual.

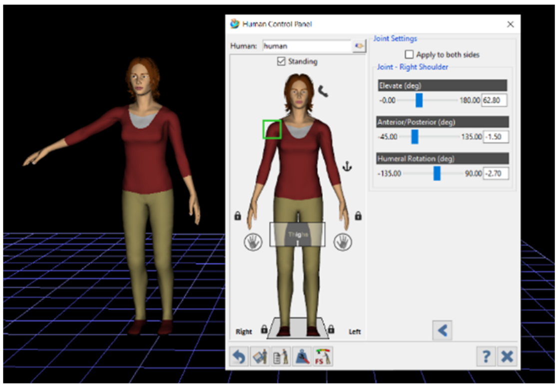

Figure 2: Shoulder Joint Settings for Jane.

3.4 Case Scenario: Industrial Partner

Bocar Group is a German – Mexican group that started its operation in Mexico City in 1958. Their first products were fuel pumps and carburetors. Nowadays, Bocar Group is a product developer and a full-service supplier of aluminum and plastic parts products for the automotive industry. Bocar Group employs 6,000 workers in 11 facilities for production in Mexico and 5 engineering and commercial offices around the globe.

The group is divided into three primary divisions: a) Bocar focus in plastic and aluminum manufacturing parts and complex assemblies for automotive applications, b) Auma develops and produces aluminum die-cast products and c) Plasti Tec produces plastic injection-moulded parts. Bocar Group has a collaborative network with the institution, which allows students to make practices in their facilities.

3.4.1 Problem Identification

Among the practices carried out by undergraduate students, it was included the ergonomics study of the operators of a line of machining processes for aluminum parts at Bocar Group. The students would observe the different production processes in the company and analyze different operations to determine the ergonomic implications existing in said operation.

An issue detected was that the machines were designed for a percentile with anthropometry other than the machinery and it was necessary to identify if this might arise a possibility of generating some long-term musculoskeletal injury. To this end, the students measured the workers at each station and used the ergonomics modules of Jack to analyze the workers' postures during operations.

3.4.2 Data Gathering and Data Capture

Students were divided into teams of 3 or 4 members to analyze the processes of loading and unloading material on the company's machines. They used a first-generation Microsoft Kinect sensor as an infrared camera to detect the movements of the operators and the software Jack allowed to record the postures immediately (Figure 3).

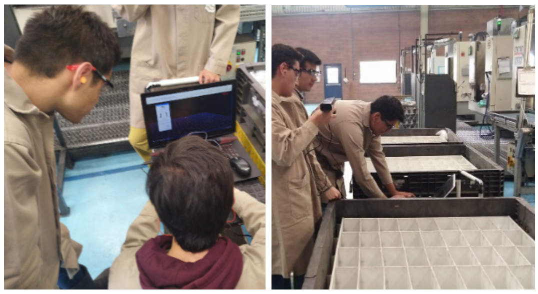

Figure 3: Left: The measurements of the workers is parametrized in the software. Right: the students capture the movements and positions of the workers with a Kinect.

Within the software, the operator must be parametrized, entering data such as weight and height. A feature of Tecnomatix Jack is that it has a database of anthropometric characteristics from different countries and regions of the world, but if the operator characteristics do not match with the models in the databases, a custom profile can be created (Figure 4).

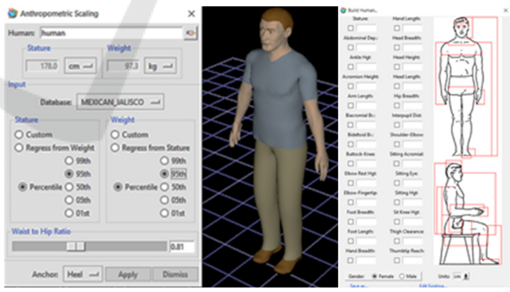

Figure 4: Anthropometric measurements in Jack.

3.4.3 Data Analysis and Results

The students analysed the data collected and observed the ergonomic implications of performing different operations. The OWAS analysis of the postures captured was made and the results were presented, as part of the final project for AIA. The analysis from the students shows that some postures can be performed by the operator to see if there is discomfort or not (Figure 5).

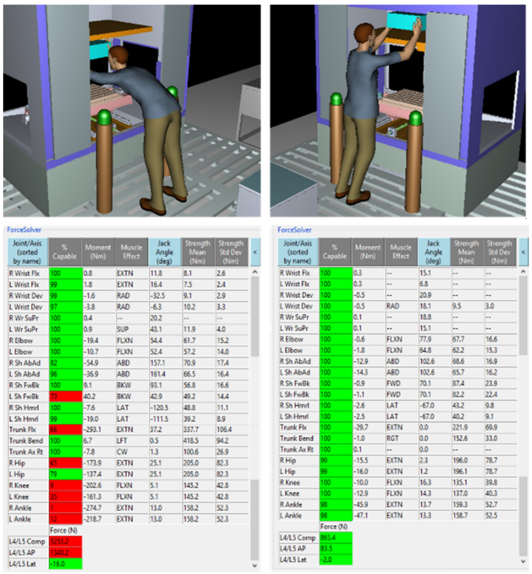

Figure 5: Example of a non-ergonomically appropriate position (left) versus an ergonomically appropriate position (right) validated with the help of the software. The red indicators on the right side indicate posture issues.

The students identified some repetitive operations that generate stress in body joints while (hip, knee, ankle) due to a non-skid element that was placed on the floor. The proposed solution was to adjust the height of the worktable according to the thickness of the non-skid element or to replace it.

4 ASSESSMENT IN PRODUCT DESIGN

Mechatronic Design and Mechatronics Laboratory are project-oriented courses in which students must develop an engineering product and the processes associated with its design and manufacture (Esqueda et al., 2019). To this mean, they identify a need within a target population and carry out several design iterations around their needs.

Regarding anthropometric and ergonomic considerations, they were given liberty to include what they feel adequate, without any particular requirements. The degree of development of this activity had no influence in the grade of the students since the objective was just to validate their understanding of the topics. Yet, we defined the following score to assess their understanding:

Table 1: Score table to assess ergonomics and anthropometrics degree of development.

	1 point	2 points
A. Association of design and target population	They included one kind of user	They considered more than one kind of users
B. Dimensions of the target population	Got data from a book or digital source	Gathered experimental data
C. Weight of their target population	Got data from a book or digital source	Gathered experimental data.
D. Their design was created by percentiles:	An average user (50%) or fitting a large person (100%)	Design can adapt to diverse percentiles (usually 5%-95%)
E. Weight limits of the device, ergonomic handles or adequate position to lift it	One of the past elements was taken into account in their design	Two of the past elements were taken into account in their design
F. Ergonomic fitting and/or easy reaching to certain parts	One of the past elements was taken into account in their design	Two of the past elements were taken into account in their design
G. Design iterations with anthropometric data or ergonomics	They iterated their design taking one parameter of their target population.	They iterated their design taking several parameters of their target population

4.1 Example Projects

The following two examples are given to present the work carried out by the students.

4.1.1 Earthquake Detection System

The students of this team proposed a system to detect earthquakes, a phenomenon that is very common in Mexico City. The problem they had identified was that, in several seismic communities, there was no anticipated public alert as there is in Mexico City. They also identified that even in Mexico City, there were a vulnerable group of people: those with hearing impairment.

Their device would then be composed of two components: one docking station that would be responsible for getting earthquake alerts (either by an internet connection to Mexico's Seismological Service or by an accelerometer's response whenever there was no connection available) and a bracelet connected via Arduino's Bluetooth Shields HC-05 and HC-06.

If an earthquake was detected, the docking station would turn on some flashy LED lights and a sound alert for the people in the house without the hearing impairment. Likewise, it would send an alert to the bracelet so it would vibrate, letting the person with the hearing impairment be aware of the danger. The docking station would also serve to charge the battery of the bracelet.

For their anthropometric analysis, they researched the 5-95 percentiles of the wrist circumferences for two groups of population: kids between 5 and 12 years, and teens/adults over 12 years. They also considered an ergonomic aspect: the fact that certain people wear their wrist straps with different levels of tightness (see Figure 6).

To validate this, they measured experimentally the wrists of 10 kids and 10 adults at different positions. This information allowed them to define the placement for the holes in the strap for both the kids and the adult version (see Figure 7).

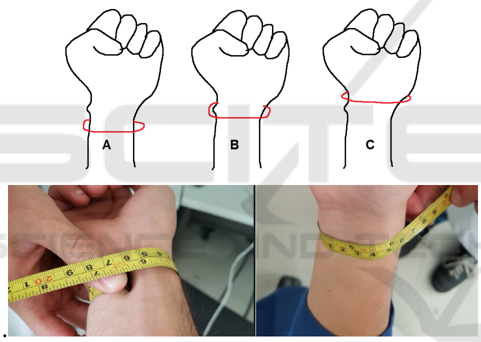

Figure 6: Positions of the strap for the wrist (top) and experimental measures to complement their data (bottom).

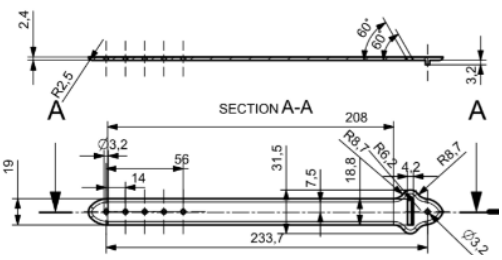

Figure 7: Part of the Technical Drawing for one version of their straps. Units in mm.

Some insights obtained from asking their target markets were that the bracelet should be lightweight and both devices should be safe. This motivated them to take out a screen they have previously considered to reduce weight and redesign both of their devices without sharp edges.

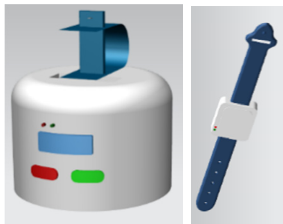

Figure 8: Final proposal of the docking station (left) along with its compatible bracelet (right).

For the docking station, they would include two big luminous buttons (one red and one green) to turn on/off the alert manually if needed. The screen would also display information regarding the earthquake.

Finally, they also considered that placing it in the bureau next to the bed would be optimal for reaching it either while standing up or while laying down in bed, which would be advised in an instruction's manual to their end-users.

4.1.2 Smart Lunchbox

This project was a solution after detecting bad nutrition habits of students and workers in Mexico. To solve this, some students proposed a lunchbox that would interact with an app to promote healthy dietary habits. (Figure 9).

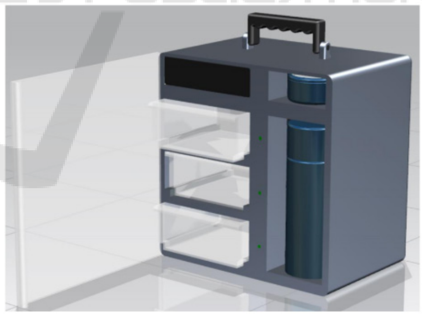

Figure 9: Render of the smart lunchbox.

The app would register information regarding their nutrition and exercise habits, as well as information about their weight, height and other factors that could let nutritionists identify a healthy diet for them. The app would then propose what to fill the lunchbox compartments with, and control the unlocking of those compartments at the right time for eating to reduce the chance of people cheating in their diet.

Their ergonomic analysis would focus on people ranging the ages of 18 to 45 years old. With data obtained from Avila et al. (2007), summarized for women in Figure 10, they obtained the data of the 5-50-95 percentiles for different dimensions they found useful for their design (height, the front reach of the arm, sitting height, grip diameter and knuckles height).

age	student/worker	height			front arm reach			sitting height			grip diameter			knuckles height		
percentiles		5	50	95	5	50	95	5	50	95	5	50	95	5	50	95
18	student	1478	1574	1666	537	600	663	793	840	885	34	39	44	639	695	751
19-24	student	1485	1586	1690	549	622	704	785	840	886	34	38	44	638	695	751
18-65	worker	1471	1570	1658	631	684	741	791	831	879	40	45	50	663	704	769

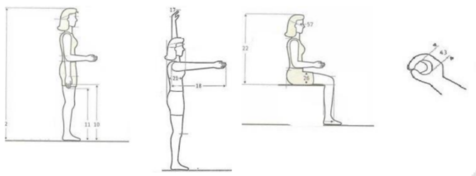

Figure 10: Summarized anthropometrics information for the female population between 18-65 years old as obtained from Avila et al. (2007).

With that information, the students identified the positions in which their target markets would use and lift their device (Figure 11), in order to define the dimensions for optimal use, as well as a weight limit when empty (500 g) to reduce the effort of lifting it. They grip diameter and knuckles height data was used to define the length and diameter of the handle.

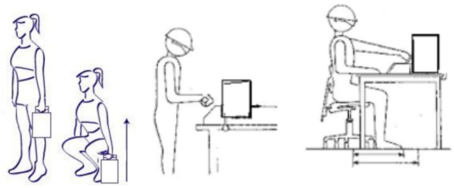

Figure 11: Recommended positions for lifting or using the device.

4.2 Scores

Table 2 shows the scores assigned for the projects presented during 3 consecutive periods of 2019: the semester going from January to May had 6 teams, an intensive summer period in June-July with 4 teams, and another semester going from August to December with 3 more teams. All teams were composed of 4 to 6 students. The score of each column relates to the categories given in Table 1, where a 0 means no consideration at all was made by the team.

To validate if there was a meaningful connection between the activity of the optative course of Advanced Industrial Automation and their understanding in a different context (i.e. product design instead of machine design), several projects were compared, shown in Figure 12. The x-axis represents the number of students enrolled in the optative course independently of the semester in which they were enrolled in the mandatory courses (which had a total of 62 students), while the y-axis shows the score obtained in their ergonomics and anthropometrics assessment presented in Table 2.

Table 2: Score table to assess ergonomics and anthropometrics degree of development.

Project	A	B	C	D	E	F	G	Score
Coffee-Delivery guided robot	2	1	0	0	0	0	0	3
Autonomous inventory robot for supermarket warehouses	2	1	0	1	0	1	1	6
Tennis-ball picker guided robot	0	0	0	0	2	0	1	3
Wrist wearable to avoid truckers from getting sleepy	1	1	0	2	1	1	1	7
Baby cradle with automatic rocking system	2	1	0	1	0	0	1	5
Closet that scans the available clothes and proposes combinations through an app	0	0	0	0	0	1	1	2
Intelligent modular power strip	0	0	0	0	0	0	0	0
Earthquake detection docking station and compatible wrist wearable	2	2	0	2	0	2	2	10
Airbag vest for motorcycle riders	2	1	0	2	0	2	1	8
Marking device for home burglars	1	1	0	1	0	1	1	5
Smart lunchbox with nutritional follow-up	2	1	1	1	2	2	2	11
Plastic bottles melting machine to generate 3D printing filament	0	0	0	0	0	0	0	0
Interactive braille book with compatible toy	1	1	1	1	1	0	1	6

While more information is required in order to statistically validate this result, we can observe that there seems to be a correlation between the number of students taking the AIA course, and the degree of development of ergonomics and anthropometric design.

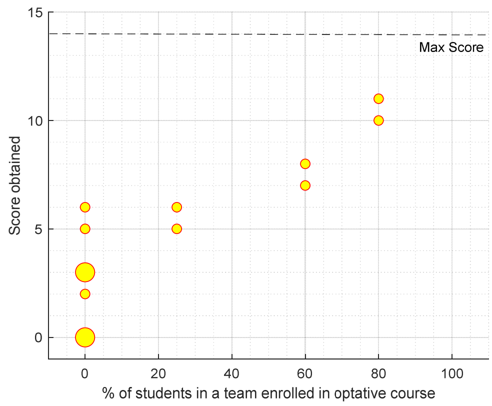

Figure 12: A comparison of the % of students in a team enrolled in the optative course versus the score obtained. A smaller circle indicates a single team having that score and percentage of participants a bigger circle indicates two teams shared the same situation.

5 DISCUSSION & FUTURE WORK

Even if the sample is small, it can be observed that teams with 0-1 person enrolled in the AIA course developed fewer concepts than teams with 3-4 members enrolled in such a course. Having no impact on their grade confirms that the better the concepts were understood, the better the analysis they did.

However, even if it simplified learning of the concepts, none of the student teams did a virtual ergonomic analysis, possibly due to time restrictions with the graded deliverables on the project and the unavailability of the hardware/software combination in their own computers. Moreover, it would be interesting to see their degree of development when certain restrictions are set as graded.

The next step of this research considers doing a small workshop as part of the mandatory courses, in which the students can use Kinect and Jack to evaluate postures using the OWAS assessment while they are assembling their prototype. Moreover, we might plan an experience with a company having a high rate of musculoskeletal disorders to propose simple product design solutions to mitigate those risks.

Another step that needs to be implemented is the design of a grading tool that assesses the understanding of Ergonomics, Anthropometrics, and the use of simulation software to anticipate WMSD.

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