COMPASS: CONTINUOUS OBJECTIVE MULTIMODAL PAIN ASSESSMENT SENSING SYSTEM DESIGN

A Thesis Presented

By

Veersinh Patil

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ABSTRACT

Pain is an abstract concept which varies from person to person. The current pain measurement techniques rely solely on a patient’s tolerance to pain and the ability to communicate the said pain. Hence, there is a need for a comprehensive and objective system to evaluate pain. This need stems from the general difficulty doctors and patients experience when self-reporting their pain levels, as well as cases where the patients may be untruthful or unable to communicate their pain levels. An objective system, one used in parallel with the current subjective methods, may help doctors effectively manage pain and prescribe the correct medication, as well as the appropriate doses. This thesis will study and evaluate the similarities and differences between chronic pain and acute pain through testing various biosensors such as electroencephalogram (EEG), respiration rate (RR), galvanic skin response (GSR), electromyography (EMG), etc. This system of sensors will be tested on approximately thirty subjects here at Northeastern University, and thirty patients with chronic lower back pain at the Brigham’s Women’s Hospital, pending the approval of the IRB. The patients will be instructed to go through a series of maneuvers and the sensors attached will record the pain level of the subject. From there, the collected data will be analyzed to determine any statistically significant sensors. Along with the above-mentioned points, this thesis focuses on designing and justifying an appropriate apparatus to carry all the equipment in an efficient and functional manner to make the testing, data reading and evaluation as easy and consistent as possible for the user and the patient.
ACKNOWLEDGEMENTS

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I would also like to thank Dr. Mingxin Yu, former IHMS member and currently Associate Professor from Beijing Information Science & Technology University; Dr. Robert Edwards, Pain Psychologist, Brigham and Women’s Pain Management Center; Li Wang, Yikang Guo, Ph.D. Graduate Assistants working at the IHMS lab, as well as the undergraduate Capstone Design team and undergraduate assistants from the IHMS lab, Shaikha AlAsousi, Mohammad Alsumait, Omar Halabi, Juliana Segares, Grace Strickert for their help in collecting experiment data.
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1. Introduction

1.1 Problem Statement
Pain involves a complex interaction between specialized nerves, your spinal cord and your brain. Imagine a complicated traffic system, with on-ramps, different speeds, traffic lights, varying weather and road conditions, a traffic control center, an emergency response system, and more. The vehicle you're in also makes a difference, because the experience of pain varies from one person to another. Pain is both physical and emotional. It involves learning and memory. How you feel and react to pain depends on what is causing it, as well as many personal factors. There are two major categories of pain. Pain can be short term (acute) or long term (chronic). For those with chronic pain, it is something that must be constantly monitored, managed, and treated so it does not interfere too greatly with day-to-day life. Accurately detecting pain and assessing its severity is essential to effectively managing pain. Thus, the medical community is in need of a method to consistently measure pain. Currently, the predominant methods require subjective reports by patients and involve large amounts of variation due to untruthful patients and differing interpretations of these scales. An objective pain measurement is needed to replace these subjective reports and to improve the practices of pain management.

1.2 Thesis Goal
The goal of the thesis is to contribute to development of the pain sensing system for use in a clinical setting where frequent, objective assessment is needed to ensure safe levels of pain management. The thesis primarily focuses on the design of the cart that will help carry all the equipment and devices necessary to make the research possible. The research pertains to assisting and helping with studying the differences and similarities between chronic pain and acute pain, and testing the different biosensors against one another. The cart design contributes to convenience and efficiency as well as providing a time saving factor.
2. **Background**

2.1 **Patient background**
Low back pain is chronic if it has been present for greater than three months. Chronic Low Back Pain may originate from an injury, disease or stresses on different structures of the body. The type of pain may vary greatly and may be felt as bone pain, nerve pain or muscle pain. The sensation of pain may also vary. For instance, pain may be an itching sensation, burning, stabbing or tingling, sharp or dull, and well-defined or vague. The intensity may range from mild to severe. Lower back pain is a very common disorder, affecting almost 80 percent of adults throughout their life. It has been proven that it affects men and women equally. There was a problem with finding a specific diagnosis to this condition, and thus, it was found to be more common to classify in accordance with the duration of the pain (i.e. acute, subacute, or chronic). For the purpose of this experiment, the main focus will be on chronic lower back pain. Today, chronic Low Back Pain (cLBP) is seen as a recurring or persistent condition that fluctuates over time. Very little is known about the long-term course and the variety of patterns regarding cLBP. Due to the variations in the levels of pain and the numerous reasons for the discomfort, it makes it harder for the doctors to accurately measure the patients pain to help them manage it.

2.2 **Present Pain Assessment Methods**
The methods that exist today in measuring chronic lower back pain are purely subjective to the patient. Physicians can observe an individual who is profoundly disabled by seemingly low pain intensity, and other cases where an individual maintains a productive and fulfilling lifestyle, despite experiencing a high pain intensity.

Doctors solely rely on what the patient has to say about their pain to not only understand the pain but also to try to figure out the correct treatment for the said pain. Based on the differences in every single person, it is hard to gauge and judge the pain as there is no other way, in a clinical setting, that measures the pain from an objective standpoint.
The Verbal Pain Intensity Scale is a spectrum that ranges from “No Pain” to “Worst Possible Pain” and asks the patient to report their pain by selecting one of the discrete descriptions of pain. One of the shortcomings of this scale is the limitations of adjectives given. Patients are forced to select one of the adjectives listed on the scale, even if it may not accurately depict the pain they are experiencing. Additionally, the spacing of increments of pain appears to be equal. However, there is no evidence stating that difference between “mild pain” and “moderate pain” is equivalent to the difference between “severe pain” and “very severe pain”.

The Visual Analogue Scale also ranges from “No Pain” to “Worst Possible Pain.” This scale requires that patients point to a location along the spectrum to report their level of pain. This requirement limits the capability of this scale for patients that have limited motor skills. A strength of this scale is the strong ratios between pain reporting. A change

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**Figure 1: Current Pain Assessment Scales**

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The Visual Analogue Scale also ranges from “No Pain” to “Worst Possible Pain.” This scale requires that patients point to a location along the spectrum to report their level of pain. This requirement limits the capability of this scale for patients that have limited motor skills. A strength of this scale is the strong ratios between pain reporting. A change
of pain level from 50 to 25 on this scale has been shown to represent that pain has been approximately halved.

The Numeric Pain Intensity Scale asks patients to report their pain by assigning a numeric value to it. On this spectrum, 0 represents “No Pain” and some upper limit, 10, 20 or 100, represents “Worst Possible Pain”. An advantage of this scale is that patients only need to respond verbally, no movement is required.

2.3 Existing Pain Measurement Devices
There is a constant advancement being made to develop objective pain response devices. Some of the new ways to measure pain are: biopotential, autonomic nervous system, biomarkers, neuroimaging, and composite algorithms that combine several of the methods. Several physiological responses can be associated with pain in the body. Based on previous conversations between anesthesiologists and clinical collaborators, specific biosensors were chosen as potential indicators of chronic Low Back Pain (cLBP).

Electroencephalograph (EEG): This device measures electrical brain activity via 32 electrodes placed on a patient’s head. These electrodes measure the amplitude of voltage signals passed through the channel, which will return data based on the placement of the electrodes. The EEG can have several different configurations or montages: bipolar montage, referential montage, average reference montage, and Laplacian montage. The raw data will be transformed into another format based on the montage type. For example, in the average reference montage configuration, “the outputs of all the amplifiers are summed and averaged, and the averaged signal is used as the common reference for each channel”. Because of their growing popularity, EEG studies have been very successful in understanding brain activity, and therefore are a complement to this project.

Respiration rate (RR) is a measure of increased body activity and may be related to pain experience. This measure alone is not proven to be an important fatigue measure, but studies have shown that if it is analyzed in unison with heart rate variability, it can be a powerful indicator of discomfort. To measure RR, a respiratory biofeedback sensor is placed around the patient’s abdomen and chest to monitor the breathing pattern.
Heart rate has been shown to be a relatively poor indicator for change in pain level, but when interacting with other physiological responses (such as respiratory rate), can prove to be useful. To measure heart rate, a Blood Volume Pulse (BVP) sensor will be used. This device is attached to the patient’s middle finger. Although Heart Rate Variability (HRV) has been clinically used to predict or monitor heart conditions, the BVP sensor can be used in an everyday setting to reflect an individual’s stress level, or in this project’s interest, pain level. Figure 2 shows a patient being monitored by the EEG, Pupil Diameter (a test that did not prove to be indicative of pain by the previous COMPASS group), and Respiratory Rate. Another device to be used throughout the experiment is going to give the reading of the blood pressure of the patient before the experiment, during, and after the experiment. This device is going to be attached to the patients.

![Sensor Application 1](image)

**Figure 2: Sensor Application 1**

Galvanic Skin Response (GSR), also referred to as Electrodermal Activity, is the level of sweat gland activity from a hand, which correlates to the activity of the nervous system. GSR is measured using a skin conductance sensor attached to the index and ring finger.
Currently, GSR is used to measure stress levels in several situations. It was historically used to quantify soldier stress and was compared to two other measures of stress, survey and salivary amylase, while soldiers were immersed in simulated environments. Pain has shown to increase activity of the nervous system, so using GSR as a measure of pain is a viable option.

Muscle contraction is a very common reaction to pain. Electromyography (EMG) has been recently used to measure muscle contraction in the lower back, thought of as a possible indicator of cLBP. This method places electrode sensors along the patient’s arm and monitors the electrical activity that causes muscle contraction. An EMG device is used to record the strength and frequency of electric pulses, showing a great addition to this project’s dataset. Figure 3 shows a picture of GSR, BVP, and EMG biosensors acting on the pilot test subject.

![Figure 3: Sensor Application 2](image)

Lastly, a person’s body temperature typically drops when he or she is under stress. There are several experiments that indicate that body temperature can change when exposed to a strong static magnetic field, or when there is a change in humidity of the body.
However, even if it has not been used extensively as a potential marker for pain, it can still provide important data for this project’s analysis. Skin temperature is measured using a skin surface thermometer, which is attached to the back of the hand, as shown in Figure 4.

![Sensor Application 3](image)

Figure 4: Sensor Application 3

2.4 Experiment Briefing
This project is a continuation of a capstone project that concluded in Spring 2018 and in collaboration with Capstone team Spring 2019. The first COMPASS team tested the device in a non-clinical setting. This experiment was conducted on healthy students from Northeastern University and simulated acute cold pain.

2.4.1 Experiment Overview
The acute cold pain test was conducted on 28 subjects, three times and on three different days to understand the variability in the subjects reading. The seven physiological sensors mentioned above were used during the experiment along with vide for each test. For each subject, 30 seconds of baseline data was collected. Then, the subject was asked to place his or her hand in a bucket of ice water. Every 20 seconds, the subject was prompted to
give a verbal pain rating on a scale of 0-10. The test concluded after 10 pain ratings were recorded (200 seconds). If the pain became too extreme at any time, the subject was able to remove his or her arm and terminate the experiment.

2.4.2 Sensors
Sensors were the main method of collecting the data for this experiment. Each sensor was attached to the patient in a non-invasive manner. The units and the rate at which each sensor collects data is specified in Table 1.

The data collected from the sensors shows the body’s physiological response or potential lack of response to the pain they are experiencing.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Units</th>
<th>Sampling Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electroencephalograph (EEG data)</td>
<td>nV</td>
<td>500</td>
</tr>
<tr>
<td>Skin Conductance Sensor (Galvanic Skin Response)</td>
<td>1/Ω</td>
<td>256</td>
</tr>
<tr>
<td>Electromyograph (EMG/Muscle Contraction)</td>
<td>µV</td>
<td>256</td>
</tr>
<tr>
<td>Blood Volume Pulse (Heart Rate)</td>
<td>Beats per Minute</td>
<td>2048</td>
</tr>
<tr>
<td>Surface Thermometer (Skin Temperature)</td>
<td>°C</td>
<td>256</td>
</tr>
<tr>
<td>Abdomen Band (Respiration Rate)</td>
<td>Breaths per Minute</td>
<td>256</td>
</tr>
<tr>
<td>Tobii Pro Glasses 2 (Pupil Diameter)</td>
<td>mm</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 1: Sensor Unit and Sampling Rate

First, the data was examined for trends between reported pain levels and the physiological inputs. However, the different sensors came in at different sampling rates, as shown in Table 1. The data was transformed because they are at different sampling
rates and pain measures are recorded every 20 seconds for non-clinical data. After transforming the data and determining any trends, only sensors that show a relationship with pain were continued to be used.

2.4.3 Initial Procedure and Improvements
Throughout the span of the project, there have been a few changes to the way the experiment is performed. This has impacted the experiment in a very positive manner. The three critical factors that were changed in the experiment were brought about with the knowledge and expertise of Dr. Mingxin Yu, former IHMS member and Associate Professor at the Beijing Information Science and Technology University, Dr. Robert Edwards, Pain Psychologist at the Brigham and Women’s Pain Management Center, Professor Yingzi Lin and the team, and are explained below.

Initially the subject had to immerse their hands in almost freezing water which often caused a stunning factor, which forced the subject to stop the experiment sooner. The change made to this note was starting the experiment with the subject’s hand immersed in room temperature water and then gradually adding ice to reduce the temperature of the water until the desired temperature is reached. The initial experiment was also conducted at almost freezing water which did not give the subject an opportunity to keep their hands in the water for long and the team could not get a reading on a larger time scale. Gradually adding fixed amount of ice at fixed time interval helps get a more detailed pain reading. The last crucial factor that was changed was the time span of the study. The initial process conducted the tests on the subject just one time. The new process conducted the experiment over a three day period on the same subject. This helped in getting a consistent result and eliminating various unnecessary variables, leaving the team with a clean result.

2.4.4 Pilot Testing
A Pilot Test was conducted using a Northeastern graduate student as our subject. The data was collected over a span of three days using cold pain testing procedure. This test was conducted while working with Prof. Lin’s team and data was collected over the time span of three days. During the pilot testing, a lot of problems and inefficiencies were found, so process improvement concepts were applied to help minimize those issues.
Some of these improvement concepts consisted of standardizing the process in terms of how often ice was added to the bucket and how much ice was added. It was also observed that the set-up time was a big factor. There were issues in transitioning between subjects in the later stages when there were multiple subjects scheduled back to back. Along with these and a few other speed bumps, accountability of the sensors and equipment was also stressful. These points and more were used as criteria’s while designing a cart ideal for the experiment which is explained later in the paper.

2.4.5 Experimental Procedure
This section describes the step by step experimental procedure used while performing the experiment. The main steps involved in the procedure were, setting up all the bio sensors on subjects, preparing the bucket of room temperature water, preparing the bucket of ice, starting the clock and sensors and taking pain reading every 20 seconds and adding ice until the subject cannot continue of does not change the reading for over 60 seconds. The average time stamp of the procedures conducted in the experiment were noted and are described in Table 2.

<table>
<thead>
<tr>
<th>STEP</th>
<th>ACTION</th>
<th>TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>START TIMER</td>
<td>0:00</td>
</tr>
<tr>
<td>2</td>
<td>START BIOSENSORS</td>
<td>0:10</td>
</tr>
<tr>
<td>3</td>
<td>START EEG</td>
<td>0:18</td>
</tr>
<tr>
<td>4</td>
<td>START CAMERA</td>
<td>0:30</td>
</tr>
<tr>
<td>5</td>
<td>START VIDEO &amp; TOBII</td>
<td>0:40</td>
</tr>
<tr>
<td>6</td>
<td>TAKE BASE DATA</td>
<td>0:40</td>
</tr>
<tr>
<td>7</td>
<td>SUBMERGE HAND</td>
<td>1:10</td>
</tr>
<tr>
<td>8</td>
<td>TAKE PAIN READINGS</td>
<td>1:30+</td>
</tr>
</tbody>
</table>

Table 2: Experimental Procedure Time Stamp
2.4.6 Experiment Result
The first phase developed a proof-of-concept model that indicated there is some potential for measuring pain. Ultimately selecting random forest regression as the preferred model, data analysis showed that tree-based models were consistently the best approaches. During testing, subjects were able to deliver frequent and reliable subjective pain ratings. This indicates the viability of using subjective pain ratings as the standard with which to align device measurements in future testing.

3. Cart Design Development
From the first phase of the development process until the end of the experimental phase, a design for the cart was engineered. This designed was developed and modified based on the necessities of the experiment and the observations made during the testing.

3.1 Design Requirements
Out of the multiple design layouts engineered for the experiment, the top three were qualified based on the current experiment setup of sensors and other equipment’s needed for the experiment. This revolved around the ease of access to the sensors and proper storage. Respiratory rate, and Eye tracking sensor are delicate sensors and need to be stored properly with care. This was an important feature to consider while designing the cart. Also, the other sensors such as the EEG sensor take time to set up. During the initial experimentation and later stages in the experiment, the team realized that reducing this time was crucial during the setting up of the experiment. Hence storing the EEG sensor in such a way that the it could be set up easily is very important. Not only that but considering a scenario where there are multiple subjects are tested back to back is necessary. In such a case of back to back testing of subjects, storing the EEG and other sensors away in the cart and removing it for the next patient wastes quite a bit of time and limits the number of subjects that can be tested. Hence it was necessary to make an adjustment or an addon to the cart where every sensor would have a quick turnover if necessary, without having to store them between tests. It was crucial that this in between test storage is easily accessible and the devices and sensors can be kept separately to make it easy to attach them back to the new subject and achieve the goal of saving time. This was considered while selecting the design as few of the seven criteria’s that the final design should meet to have an optimal cart for the experiment. The above-mentioned
requirements add to the ease of experimenters to conduct the experiment while also valuing the subjects time. They also provide accountability for the instruments as every sensor has a separate storage space along with the bucket required to hold the cold water. Although these criteria are important, they are not everything. There are other factors that were noticed and need to be considered for the design. As the cart is also to be used in hospitals, some critical factors to be considered are quietness and maneuverability out of consideration to the other people and patients in a hospital. These were added as requirements to the design. All these seven constraints required to meet the design constraints are listed below in the cart setup with a detailed description and reasoning of including them as one of the main necessities to design the cart.

3.2 Cart Setup
While conducting the experiment, ease of access and convenience are two of the most important factors in the procedure. These two inevitably contribute to increase in efficiency while conducting tests which in turn will not only save the researchers’ time but also doctors and hospitals in the longer run.

The setup required to carry the pain measuring devices had to follow a few certain constraints. The most important of these constraints that were kept in mind while designing the cart were:

- Proper and safe storage for all the equipment: The sensors and equipment used in the experiment are expensive and cannot be mishandled. The equipment should be properly cared for not only during the experiment but also after the experiment while they are being stored.
- Easily accessible by one or multiple people: Time to set up the experiment is crucial not just during research but for the hospital staff, doctors and patients as well. Multiple people being able to help set up the devices at the same time will be efficient.
- Good storage capacity: Along with safe storage of the equipment, it is ideal that each equipment has its own space. This not only saves time while setting up the experiment as it is known where everything is but also acts as a check to make sure all the required devices are with the experimenter or the staff.
• Maneuverable: As the cart is going to be moved from patient to patient multiple time every day, it is necessary that the cart is not only maneuverable but also light.

• Fit through a single sided (office) door: Although this does not seem to be a critical factor, it is one of the most important constraints to remember. The cart should be able to navigate to a single sided size door. Without which it would be impossible for the cart to go from room to room.

• Quiet (hospital use): Having a loud, squeaky cart would be counterintuitive as hospitals are places where people need rest and quiet. Having a cart that is light and maneuverable goes hand in hand with this idea.

• Durable: Durability is the key to the cart. Breaking down is going to put a halt on the entire system which is going to lead to other problems. A smooth functioning reliable cart would be ideal for this situation.

3.3 Designs
There were multiple designs considered to optimize the above-mentioned categories while designing the cart. The top three of these designs are mentioned below. Along with the description, the table also provides an overview of the categories these designs met from the priority categories. It is necessary to note that all the designs were made around the patients. As patients are number one priority, ease of access to the patients and their convenience is considered as the top priority.

3.3.1 Design 1
This design consisted of a cart primarily made from tough durable plastic. As it can be seen from the drawing below, this cart does have proper and safe storage for all the equipment required for the experiment. This cart is also light and maneuverable and because it is a narrower cart, it can easily fit through any door. At the same time, it is quite and sturdy as it is made from firm plastic. It is also easily accessible by one or multiple people but because of a singular entry point, multiple people trying to move thing from or to the cart might be hard. Also, there is a lack of separation for storage. Although there is enough storage capacity for all the equipment necessary for the
experiment, a distinct lack of separation could mean a messy and time-consuming process to find the equipment.

3.3.2 Design 2
The second design a trolley cart with modifications for the purpose of the experimental equipments and the experiment. This design is entirely made of metal which makes it really durable. This cart can be accessible by multiple people at the same time which will make setting up the experiment easier and less time consuming. Along with the open spaces, the cart also has good amount of storage capacity. The open spaces is meant to store the bucket and other bigger equipments required for the experiment. It also has three drawers which makes seperation of the equipments easier but as the experiment has more than three equipments, time can be wasted looking for the equipment. This cart is maneuverable but not very light as it is made of all metal. It is narrow and has a handle on the side which will make it easier to fit through a office door. Being on four wheels makes it easier to push and pull. The wheels come with wheel lock which can guarantee the stability of the cart.
3.3.3 Design 3
The third cart design is an optimal cart design to meet all the requirements mentioned above. This design takes the positives from the first two carts and with additional features, is the ideal design for this project. As seen below in figure, this cart has proper and safe storage for all the equipment. This cart has six individual drawers, twice as many as the ones in any of the previous designs. These drawers are big enough to store every apparatus and sensor separately. This will not only help in separation of equipment but will also make it easier to find them while setting up the experiment. These drawers with tags or labels on them could also be used as a check to make sure all the gear is properly returned after the experiment. This design also has enough space on the back to carry the bucket or vessel for the patient to dip their hands in as well as has two shelves on the top for laptops and other devices. Along with these features the design comes with external hanger hooks outside every drawer for the sensors and equipment to hang from.
which will make the moving from patient to patient easier instead of storing the equipment back every time. The cart also has wheel locks which adds to the stability of the cart. The framework is metal which makes the cart durable. Also, as the frame is just an external skeleton, it makes the cart light and easy to maneuver. This design is also narrow for the cart to fit through a single office door. As a result of the light but sturdy framework, the cart is quiet while moving through the building which will surely be appreciated by the patients and the doctors.

Figure 7: Cart 3 Design
3.4 Cart Selection
As mentioned in the design justification, the carts were designed to meet the requirements of the experiment. A brief table of the requirements for the carts is shown below. This will further help finalize the decision regarding the best suitable model for this experiment.

<table>
<thead>
<tr>
<th>Quality</th>
<th>Cart 1</th>
<th>Cart 2</th>
<th>Cart 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proper and Safe storage</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Easily accessible</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Good storage capacity</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Maneuverable</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Fit through single door</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Quiet</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Durable</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 3: Cart Selection
From Table 3 above, it can clearly be seen that Cart 3 is the optimal cart design which meets all the specifications for the design. A further description of reasoning to pick this cart as the best option is mentioned below.
4. Design Justification

4.1 Optimal Design Description

Patients accessibility: Along with all the other mentioned problems addressed by this cart, it is important to note that Design 3 is the most patient reliable and accessible. This cart will be used for patients on a regular basis, multiple times a day. The table below qualifies 7 qualities that make the cart user friendly not just for the patients but for the staff accessing the cart and the other people in the facility. These seven selected qualities are listed below and were categorized as important because of the following reason.

Proper and Safe storage: It is of utmost importance that the device which is being used on the patients is properly and safely stored. Not only will this help with the ease of accounting for the device and safety but also save time in the longer run, making it easier to access the device in a fixed pattern. This will be helpful for not only the staff but also patients.

Easily accessible: As the primary function of this mechanism has to revolve around being used either for the patients or by the patients, easy and simple accessibility is a key factor in the operation of the cart. As the patients might already be weak and in pain, making the process as easy for them as possible is necessary. The need for ease of use is also true for the staff using the device as they will be operating it near the patient and would want to make the process as simple and fast as possible.

Good Storage Capacity: This functionality goes hand in hand with the first one regarding proper and safe storage. If the storage capacity is good, the operators do not have to worry about cramping the devices in the cart or worry about making in fit with one another like tetris. Having good and ample of space will not only ensure everything is stored where it is supposed to be but also give enough room to store extras and reports/documents if need be.

Maneuverability: As the cart is being used by either the patients or the assistance staff, it needs to fit in spaces besides the bed and moved around easily. The cart being maneuverable adds to the ease of the use of the cart.
**Fit through the door:** The cart is being designed to be used in hospital, hospital rooms and houses. To be able to fit into any given possible room, it is necessary that the cart fits through a single sided door; which is the smallest possible standardized door in any construction.

**Quiet:** The cart is being used near patients and in hospital where quietness is of utmost importance. Respecting the privacy and space of everyone around while using the cart is necessary and this is addressed in the selected model.

**Durability:** Durability is always a bonus especially while working in the field of medicine. Having a reliable mechanism is critical when it comes to medicine and health.

### 4.2 Optimal Cart Design Detailed Explanation

Below is a breakdown of the cart selected as the best design and explanation of the different characteristics of the cart.

Multiple views of the carts are shown and explained below for a better understanding of the design:

#### 4.2.1 Side View

![Figure 8: Cart Side View](image)
It can be seen from the side views that there is enough space in the back of the cart to store bigger containers that might be needed for the experiment. The top two shelves can also be used as desk while the experiment is being performed. The eye-catching feature from the side view are the hooks that protrude forward from the drawer. These can be used to hang the gear between experiments and can also be used to dry some of the gel-soaked equipment. The design of the hooks is further mentioned in detail later in the paper. The declining drawers prevent the equipment from slipping out or falling out if left open due to an oversight.

4.2.2 Front and Back View
The front and back view of the cart show the ease with which multiple personnel can access the cart simultaneously so as to reduce the set up time for the experiment. It also shows the handles on both sides which can help in moving the cart around in any direction. These images also help in visualizing the locks of the wheels that are placed on all four of the wheels.

![Figure 9: Cart Front and Back View](attachment:cart_front_back_view.png)
4.2.3 Cart Frame
The next image shows the raw metal framework of the cart. The entire cart is designed around this framework. This framework demonstrates the optimal use of space and strength to minimize the weight of the cart while increasing the strength. The double layered sides on the base ensure that the car can carry heavy loads while the triple support on every level shows the rigidity of the cart. This image also helps understand the amount of metal being used in the design which speaks to the light weight of the cart. The triangular handles on the top help move and carry the cart around if necessary.

Figure 10: Cart Frame Work

4.2.4 Cart Drawer Hook
The motivation for the hook design was taken from the battery connection nodes. The rectangular shape in the back enables in easy attachments in the drawer while the ridges around the spherical surfaces enables the hanging equipment from falling on in case of
sudden motion.

**Figure 11: Cart Hook Attachment**

The top isometric view of the cart below shows the hooks from a different angle for a better understanding of the placement and position.

**Figure 12: Cart Top Isometric View**

### 4.2.5 Isometric View

The isometric view of the cart shows all the features mentioned above to prove why the final Design 3 mentioned in the paper is the most suitable design for the purpose of this
experiment.

**Figure 13: Isometric View**

5. **Future Work**
The current optimal cart design is based on the requirements and necessities of the current experiment. There were some changes to the way the experiment is conducted between the first test and the last test. Although the cart is designed for adaptability to the future changes, it is important to remember to note the new updates and changes in the experiment and design the cart accordingly. Another beneficial step in designing the cart would be being able to adjust the height of the top desk. As one of the tests is a video test, the current cart height is at desk height assuming the patient or subject is either sitting on a chair or a wheelchair. Being able to make the height adjustable could be crucial to patients who cannot get out of the bed and do not have adjustable beds.

6. **Conclusion**
For the current experiment setup, since conducting all pilot testing successfully, the overall procedure has been improved. The total setup time has now been minimized to less than fifteen minutes. This allowed for the data collection to be the central focus of the group. This time can be even further optimized by including the new design in the experiment. It will also help preserve and store all the sensors easily and properly while being accountable without having to worry about losing or misplacing them, in turn being able to focus on the experiment, subjects and data. The final design is the most patient reliable and accessible. Its easily accessible and multiple people can access the cart at the same time. There is not only proper storage but also extra multi-purpose storage. The cart doesn’t not only have four wheels but has built in handles to make it maneuverable. The metal framework makes the cart durable as well as sturdy. Because of the frame structure, it is also light and easy to move about. The hook like feature adds an additional component to the cart to make the transition easier.
7. REFERENCES


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