Jon Deaton, Diana Gong, Anna Jaffe
BIOE 141B
3/12/17

# Milestone 4

## 4.0: Project Overview

*Need statement:* People uneducated about and at risk for non-exertional heat stroke in hot regions of India need a method to reduce the likelihood of experiencing heat stroke to decrease mortality.

To address our need statement, we are creating and testing a heat stroke risk prediction device. The overall concept is a system of sensors that take environmental and the user's physiological parameters and connect to a mobile phone to estimate heat stroke risk. A complete project includes sub-projects of development of algorithms for risk assessment, wearable hardware, mobile-software, and experimental testing procedures; however, we have chosen to focus only on the first and last components (depicted in Figure 1) during BIOE 141A/B.

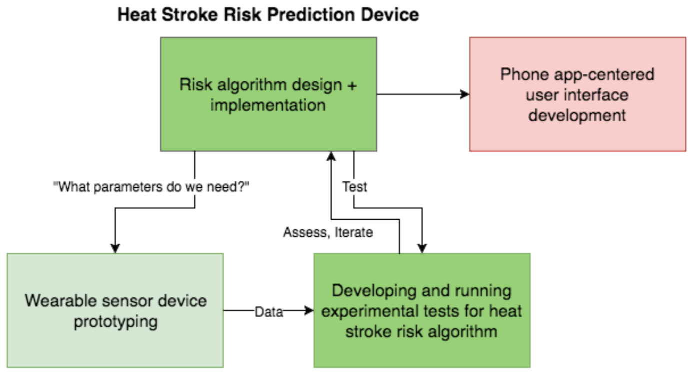


**Figure 1: Complete concept subcomponent relationships and intended focus.** Red indicates an area that we will not be addressing during BIOE 141A/B. Shades of green indicate areas that we will be addressing with our milestones, with dark green representing more focus and light green representing less focus.

We intend to implement a prototype that senses relevant parameters and need not necessarily be wearable, minimally intrusive, or connect wirelessly to a phone, as we aim to prove concept viability rather than produce a ready-to-use device. Our concept (Figure 2) involves sensors connected to a microprocessor that relays information to a computer, which predicts heat stroke risk using machine learning (ML) algorithms. By the end of BIOE 141B, we aim to have developed hardware and software that allow us to accurately sense the risk of heat stroke, as well as a series of experimental tests verifying that our device functions as expected.

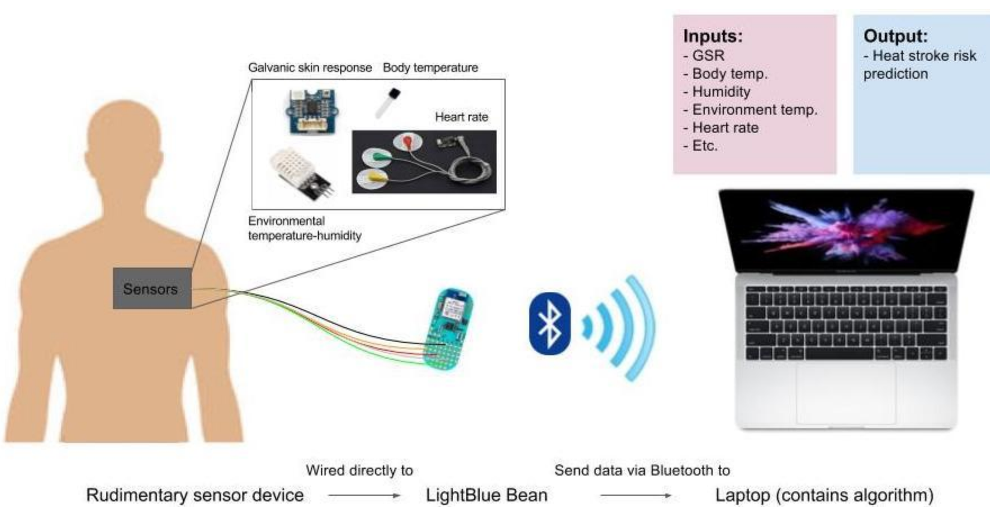


**Figure 2: Graphic depicting our concept of a heat stroke risk prediction wearable device prototype.**

**4.1: Milestone Overview**

*Milestone 4: Test heat stroke prediction algorithm.*

Milestone 4 involves testing our risk assessment algorithm. In this milestone, we aim to show that we can successfully run a test with integrated code and real-time heat stroke risk prediction for proof-of-concept, describe and critique the relevance of our test(s) for global environments with high heat stroke risk, and suggest future directions to determine and/or analyze the importance of our different sensors. Our outputs will be 1) a screenshot and video showing risk prediction in real time, 2) graphs of sensor data and risk prediction for each test. Success will be determined by the presence of these components.

**4.2: Milestone Methods**

Acronyms:
ET = environmental temperature
EH = environmental humidity
GSR = galvanic skin response
HR = heart rate
CT = core temperature
HI = heat index
LR = logistic regression

**Bean setup:** The Bean+ and sensors (SHT31 temperature/humidity, galvanic skin response [GSR], were wired as shown in Figure 3A. During testing in the Heller Lab hot room, we covered the electronics (Bean+ and sensor connections) with saran wrap to avoid getting them wet (Figure 3B).

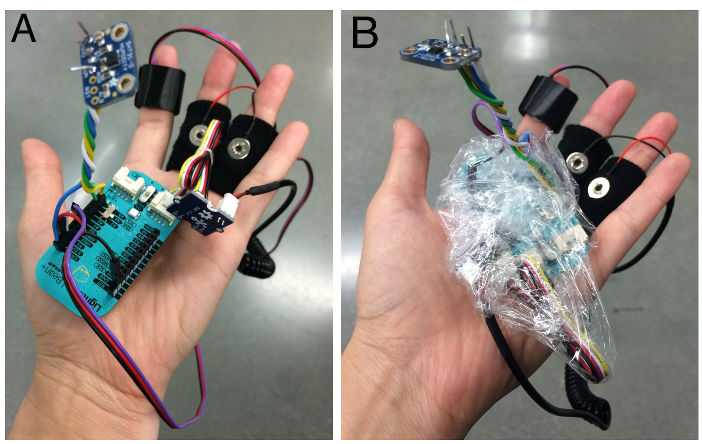


**Figure 3: Setup of sensor system and LightBlue Bean+.** During testing, the user holds the Bean in their palm. Pulse monitor is seen on index finger; GSR sensors seen on middle and ring fingers; and SHT31 temperature/humidity sensor (measuring ambient/environmental) shown sticking out ~3" away from the user's hand. **A)** Standard setup. **B)** Setup with saran wrap covering sensitive electronics for Bean+ use in Heller Lab hot room.

**Initial model testing and data generation:** We ran our prediction algorithm (integrated code in Appendix A; Figure 4; **Appendix B**) while collecting sensor data in:

- the Heller Lab (non-exertional protocol - **Appendix C**; 2/28/17)
- Shriram 112 (non-exertional protocol - **Appendix D**; 3/08/17)
- Shriram 112 (exertional protocol - **Appendix E**; 3/08/17)

We plotted data for the different prediction algorithms over time (Figures 5-12, Figures E.1-4).

```
2017-03-08 13:55:45 DN525fat.SUNet monitor[9377] DEBUG Read line: b'GSR: 468\r\n'
2017-03-08 13:55:45 DN525fat.SUNet monitor[9377] DEBUG Read line: b'HR: 78\r\n'
2017-03-08 13:55:46 DN525fat.SUNet monitor[9377] DEBUG Read line: b'ET: 24.17\r\n'
2017-03-08 13:55:46 DN525fat.SUNet monitor[9377] DEBUG Read line: b'EH: 38.61\r\n'
2017-03-08 13:55:46 DN525fat.SUNet monitor[9377] DEBUG Read line: b'GSR: 477\r\n'
2017-03-08 13:55:46 DN525fat.SUNet monitor[9377] DEBUG Read line: b'HR: 77\r\n'
2017-03-08 13:55:47 DN525fat.SUNet monitor[9377] DEBUG Read line: b'ET: 24.19\r\n'
2017-03-08 13:55:47 DN525fat.SUNet monitor[9377] DEBUG Read line: b'EH: 38.62\r\n'
2017-03-08 13:55:47 DN525fat.SUNet monitor[9377] DEBUG Read line: b'GSR: 699\r\n'
2017-03-08 13:55:48 DN525fat.SUNet monitor[9377] DEBUG Read line: b'HR: 76\r\n'
2017-03-08 13:55:48 DN525fat.SUNet __main__[9377] ERROR No data for: "Skin Temperature"
2017-03-08 13:55:48 DN525fat.SUNet __main__[9377] ERROR No data for: "Acceleration"
2017-03-08 13:55:48 DN525fat.SUNet __main__[9377] ERROR No data for: "Skin color (flushed/normal=1, pale=0.5, cyatonic=0)"
2017-03-08 13:55:48 DN525fat.SUNet predictor[9377] INFO Heat Index: 22.675 C
2017-03-08 13:55:48 DN525fat.SUNet predictor[9377] INFO Estimated current core temperature: 36.912 C
2017-03-08 13:55:48 DN525fat.SUNet __main__[9377] INFO CT Risk: [          ]    0.000605982151001
2017-03-08 13:55:48 DN525fat.SUNet __main__[9377] INFO HI Risk: [          ]    0
2017-03-08 13:55:48 DN525fat.SUNet __main__[9377] INFO LR Risk: [          ]    8.81174539468e-09
2017-03-08 13:55:48 DN525fat.SUNet __main__[9377] INFO Current risk: 0.0002 [          ]
2017-03-08 13:55:49 DN525fat.SUNet monitor[9377] DEBUG Read line: b'ET: 24.20\r\n'
2017-03-08 13:55:49 DN525fat.SUNet monitor[9377] DEBUG Read line: b'EH: 38.65\r\n'
2017-03-08 13:55:49 DN525fat.SUNet monitor[9377] DEBUG Read line: b'GSR: 687\r\n'
2017-03-08 13:55:49 DN525fat.SUNet monitor[9377] DEBUG Read line: b'HR: 74\r\n'
2017-03-08 13:55:50 DN525fat.SUNet monitor[9377] DEBUG Read line: b'ET: 24.21\r\n'
2017-03-08 13:55:50 DN525fat.SUNet monitor[9377] DEBUG Read line: b'EH: 38.64\r\n'
2017-03-08 13:55:50 DN525fat.SUNet monitor[9377] DEBUG Read line: b'GSR: 634\r\n'
2017-03-08 13:55:50 DN525fat.SUNet monitor[9377] DEBUG Read line: b'HR: 75\r\n'
2017-03-08 13:55:52 DN525fat.SUNet __main__[9377] DEBUG Saving data to: all_data_2017.03.08-13.43.12_.csv ...
2017-03-08 13:55:52 DN525fat.SUNet monitor[9377] DEBUG Read line: b'ET: 24.19\r\n'
```

**Figure 4: Screenshot of real-time heat stroke risk prediction from Terminal.** Measured sensor values from the LightBlue Bean+ that print to the Arduino Serial monitor also print in real time to the Terminal when running the prediction algorithm. In addition to printing sensor values (in green, to the right of "DEBUG"), black text shows calculations of Heat Index and estimated core temperature (latter based on heart rate data). Yellow text shows estimated risks for various models. Red text shows sensors for which no data is collected, as well as the current risk which is an average of the three risk models. All data is also periodically saved to a timestamped .csv file.

### 4.3: Milestone Results

**Heller Lab nonexertional protocol, 2/28/17:**

From our first run using the predictor in the Heller Lab on 2/28/17, we generated plots of heat stroke risk over time (Figure 5); ET, EH, CT over time (Figure 6); GSR (Figure 7); and HR (Figure 8).

Heat stroke risk was calculated over time using three different methods: core temperature (CT), heat index (HI), and logistic regression (LR). Also plotted is overall risk (as a probability [0-1]), an average of the three method, as calculated by the version of the algorithm we had during the time of testing.

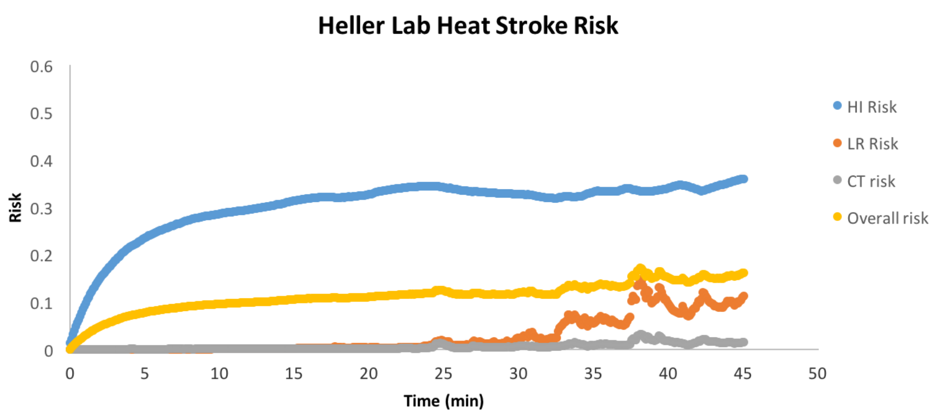


**Figure 5: Plot of heat stroke risk (0-1 scale) using various models over time.** HI = heat index; LR = logistic regression; CT = core temperature (estimate based on heart rate).

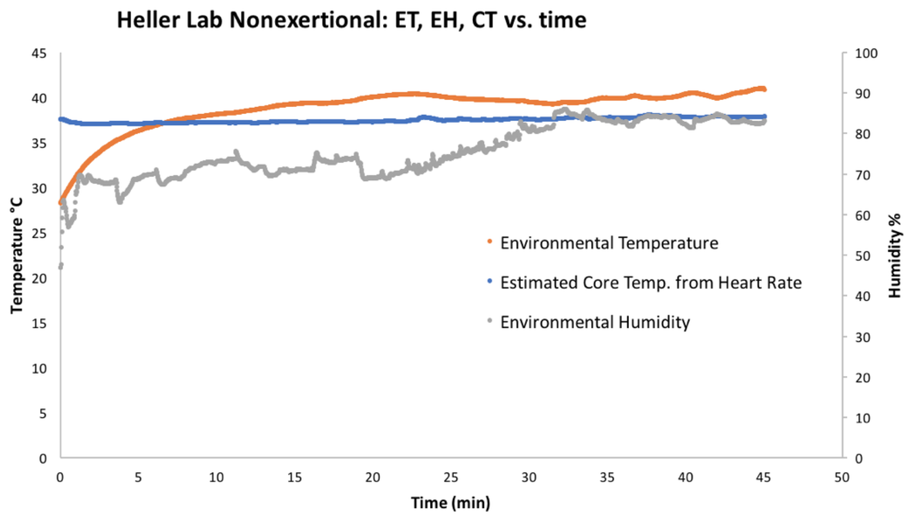


**Figure 6: Plot of Heller Lab ET, EH, and CT vs. time.** ET shown in orange, CT shown in blue, EH shown in gray.

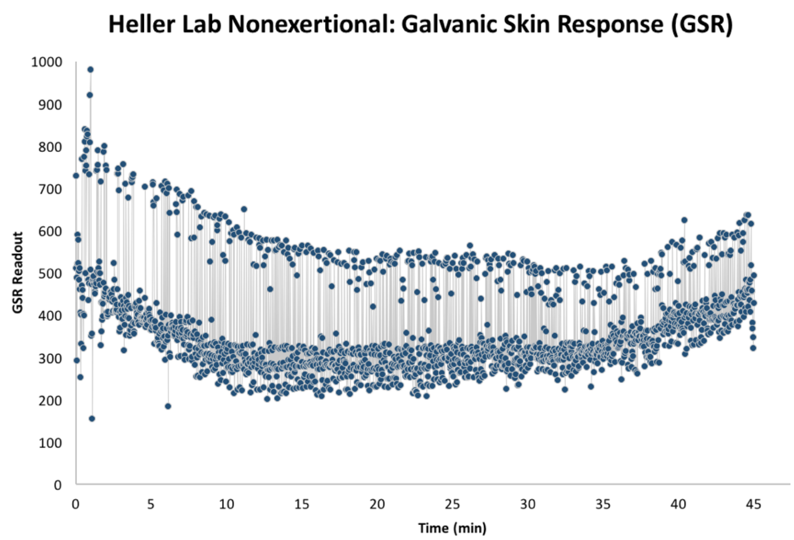


**Figure 7: Plot of Heller Lab GSR sensor data.** Measurements taken at ~0.025 min (1.5 second) intervals.

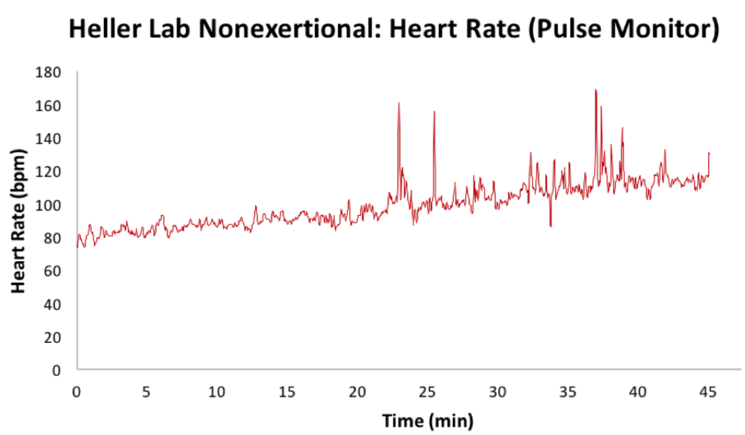


**Figure 8: Plot of Heller Lab HR vs. time.** Measurements taken with pulse monitor sensor. HR appears to be increasing linearly over time.

**Shriram 112 nonexertional protocol, 3/08/17:**
We ran our heat stroke risk assessment with a nonexertional protocol (**Appendix D**) in Shriram 112. We obtained the same set of plots as previously described: heat stroke risk over time (Figure 9); ET, EH, CT over time (Figure 10); GSR plotted over the Heller Lab data for qualitative comparison (Figure 11); and HR (Figure 12). Unlike trends for the Heller Lab run, trends for ET, EH, CT, GSR, and HR for the Shriram nonexertional run stay relatively constant (although noisy) over time.

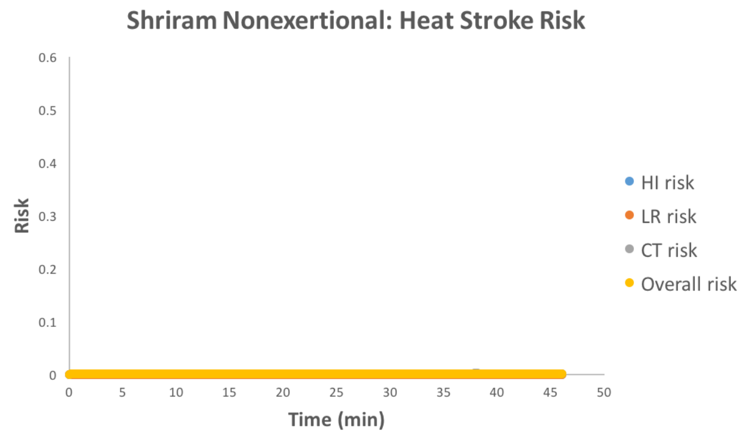


**Figure 9: Plot of Shriram 112 nonexertional heat stroke risk (0-1 scale) using various models over time.** HI = heat index; LR = logistic regression; CT = core temperature (estimate based on heart rate).

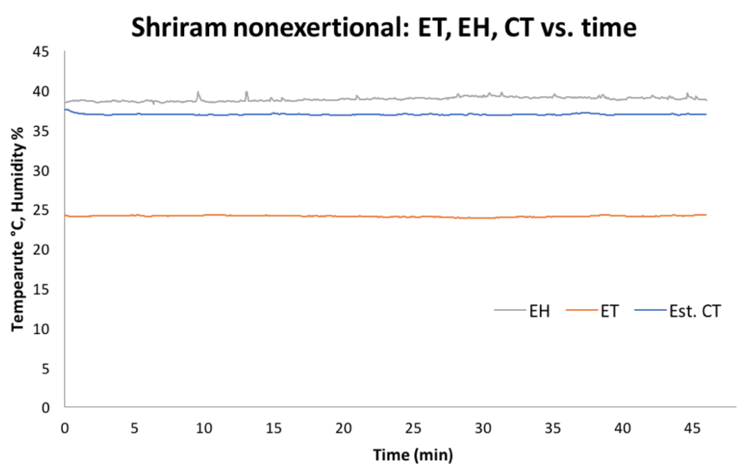


**Figure 10: Plot of Shriram 112 nonexertional ET, EH, and CT vs. time.** ET shown in orange, CT shown in blue, EH shown in gray.

We compared GSR data (Figure 12) for the Heller nonexertional protocol (hot/humid environment) with the Shriram nonexertional protocol (cool and non-humid environment). The upper sets of points in green and blue appear to be noise potentially caused by movement (see Figure E.3, Figure F.1), whereas the lower sets appear to be the true GSR values. We chose the lower set because both upper and lower sets exhibit identical trends, yet there are far more points and a smaller variance in the lower set. These properties of the lower set allows the upper set to be easily discarded as outliers and allows the use of a larger percentage of the data thereby increasing robustness of data smoothing, as compared to using the upper set.

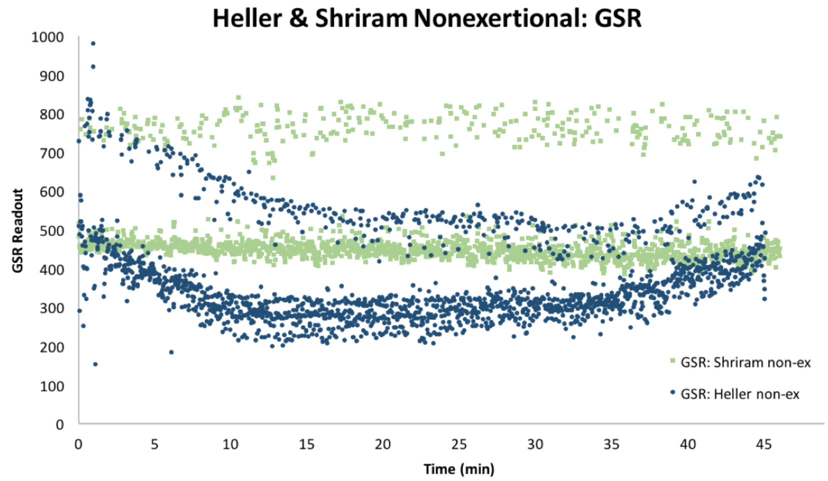


**Figure 11: Combined plot of GSR from Heller Lab 2/28 run (in blue) and nonexertional run 3/08 (in green).** Both settings have GSR measurements start at the same baseline (~500). In a nonexertional, cool/non-humid setting (Shriram), GSR remains constant; in a nonexertional, hot/humid setting (Heller Lab), GSR decreases (0-10 minutes), plateau (10-35 minutes), and then increase again (after 35 minutes). We hypothesize that the initial decrease in GSR is due to increased rate of sweating and that the increase in GSR in the last 20 minutes is due to a decrease in sweating. These results support our hypothesis that the GSR sensors can be used to sense the amount that a person is sweating. In future algorithm iterations we can factor in an estimate of risk given by GSR data by detecting if sweating has decreased without a decrease in environmental temperature. To accomplish this we could quantify some normalized ratio of the derivative of GSR and environmental temperature.

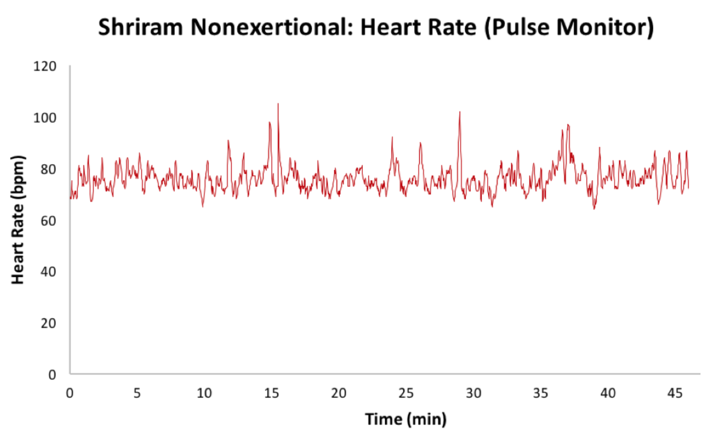


**Figure 12: Plot of Shriram 112 nonexertional HR vs. time.** Measurements taken with pulse monitor sensor.

### 4.4: Milestone Interpretation/Discussion

- 2/28/17 Heller Lab run:
  - **Successful run:** This run was successful in that we were able to integrate all sensors and read their values out in the same Serial monitor, send the Serial monitor data to Python, and continually calculate heat stroke risk in real time (Figure 4, Appendix B). Unlike the first run in the Heller Lab, the LightBlue Bean+ sent data via bluetooth during the entire run and did not get wet. We attribute the new durability of the device to saran wrapping the device to keep it dry.
  - **HI risk prediction range:** Based upon heat stroke risk results from testing our model in the Heller Lab (Figure 5), we noticed that the HI risk prediction was only at about 40% of its maximum (0.4 out of 1) by the end of the test. Given that this component of the risk calculation prediction is devoted to quantifying the relative danger of heat stroke based only on the environment that the user is in, we found it unsuitable that an environment

designed to push a person close to getting heat stroke would have a risk of ~40%. We need to modify our prediction algorithm so that HI risk would be ~100% in this particular hot environment (~40°C, 70% Humidity) and can do so by changing the dynamic range of HI to be between 30°C and 41°C HI units (perceived temperature).

- **Analysis of HI risk trajectory:** HI risk initially increases quickly before plateauing (Figure 5) because ET started at ~29°C and increased to ~40°C over time (Figure 7). The delay in reaching the maximum risk is likely due to the SHT31 temp/humidity sensor being in a garbage bag around the hands; this microenvironment may have taken time to heat up as the hands began to perspire.
    - Note: The EH inputted into the HI calculation in Python was actually off by a factor of 100, so our HI calculation is currently inaccurate and will be fixed in future iterations. At the moment, it is lower than it should be.
- **Analysis of all risk prediction models:** HI risk, CT risk, and overall risk appear to plateau over time, whereas LR risk shows greater percent change towards the end of the non-exertional heat stress test (Figure 5). We expect that an individual's real risk increases logistically with time in the same high-risk environment (rather than linearly), so LR appears to be a more accurate prediction than the other methods. In future versions of the algorithm, we could weigh LR more heavily in the overall risk prediction. Also, the CT risk assessment, by virtue of its use of the Buller algorithm[1] does not take into account environmental temperature when predicting CT from HR, thereby giving an underestimate of CT in very hot environments. We predict that we could improve the CT risk algorithm by having it increase more rapidly if the environmental temperature is high. This would have resulted in a more substantial increase in CT risk for this test. Also, considering that much of the sensor data is fed into into risk algorithms that are not LR risk, we may modify the LR risk estimate to more heavily reflect the predispositional risk of heat stroke for the user
- **Relevance of test:** The Heller Lab test (~46°C, >50% humidity) is representative of environmental heat stroke conditions because the temperature is extremely high. We know that remaining in the room for long periods of time is dangerous, which is also reflected by the protocol where the user undergoing the test is pulled out of the room upon reaching 39.5°C core temperature.
- **Future testing:** We will consider conducting behavioral analysis and/or surveys. Vinh informed us of one that he uses with a scale from -3 very cold, -2 cold, -1 slightly cold, 0 neutral, +1 slightly warm, +2 warm, and +3 hot. User response could be another factor that we include in our risk prediction.
    - We would try having the person in the hot room move or walk around to more accurately simulate people in India, who are likely not stationary.

- Shriram 112 nonexertional test:
    - **Rationale and explanation of test:** The primary goal of running this test (same protocol as Heller Lab nonexertional, but in a much cooler and less humid environment) was to validate that predicted risk remains constant and near 0, as well as ET, EH, CT, and HR. Qualitatively, we see these to be true (Figure 9, Figure 10, Figure 12).
    - **GSR analysis:** Another goal was to obtain GSR data in a different setting than in the Heller Lab. Based on data provided by the manufacturer of the GSR sensor used, we expected that perspiration would result in decreasing GSR values. When comparing GSR values in the Heller Lab test vs. nonexertional test, we found that in a cool environment, GSR values remained constant, which is consistent with a lack of perspiration; however, in the Heller Lab data, GSR values decreased, plateaued, and then increased again (possibly due to saturation of the sensors with perspiration, and then potentially evaporation; Figure 12). These data are promising in that GSR appears to be important for predicting heat stroke risk, as there seem to be significant differences between values

[1] Buller MJ et al. "Estimation of human core temperature from sequential heart rate observations." Physiol Meas. 2013 Jul;34(7):781-98. doi: 10.1088/0967-3334/34/7/781. Epub 2013 Jun 19.

over time for nonexertional protocols in hot/humid (Heller Lab) vs. cool/non-humid (Shriram) environments.

- Shriram 112 exertional test (Appendix E):
    - **Rationale and explanation of test:** The purpose of this test was to determine if the heat stroke prediction algorithm would give overestimated risk predictions during normal exercise due to increased HR.
    - **Analysis of results:** Heart rate became very high during this test causing an increase in predicted CT and thus predicted CT risk. The predicted overall risk was similar to that of the Heller Lab predicted overall risk, indicating that the following changes should be made to the prediction algorithm
        - Use acceleration data (available directly from the LightBlue Bean) paired with exercise detection algorithms to predict how much someone is exerting themselves allowing us to discount increases in HR due to exercise.
        - Update the HI risk estimation to have a lower dynamic range, so as to give a HI risk estimate of ~1 when in environments similar to that of the Heller Lab stress test environment.
- Next steps:
    - **Improve CT prediction:** Improve the prediction algorithm for CT (Buller et al. 2013) by taking into account factors other than HR. Our exertional experiment showed that exercise increases heart rate but probably does not increase CT as much as the Buller algorithm[2] indicates.
    - **Prediction from GSR:** Because GSR seems to be important for heat stroke risk prediction, we should incorporate GSR risk into the overall prediction algorithm and also look into better sensor brands that also have more extensive documentation. Further, conducting additional tests to evaluate GSR dynamics over time (e.g., does it vary from trial to trial? Person to person? How do environmental variables affect the readings?) would likely provide valuable insight.
    - **Testing risk prediction with data extrapolation:** Because it was not safe for us to increase core temperature past 39.5°C in the Heller Lab, it was not possible to obtain a real-time estimate of heat stroke risk at high CT. However, we could assume a linear increase in CT (shown in unpublished Heller Lab data), extrapolate CT values over time, and run these through the prediction algorithm. We would expect an exponential increase in risk as CT gets closer to 40°C, and if not, the algorithm could be modified.
    - **Risk output value:** Rather than outputting a risk value from 0-1 (probability), a more tangible metric would be the amount of time left before a user would likely get heat stroke. This calculated "time to heat stroke" could take into account environmental conditions such as time of day.
    - **Determining importance of different sensors:** Using time-course data collected from tests in normal environments and heat stress tests, we could estimate the relative importance of each sensor in predicting heat stroke. To do this we could examine the weights assigned to each feature used in the logistic regression, and quantify the correlations between data collected from each of the sensors and the increased risk in heat stress tests.
    - **The far future - improving prediction algorithm and increasing predictive power:** Although the Heller Lab is a decent proxy for a heat wave-like environment, using our device in India would surely be different. In an ideal situation, we would test our current device and algorithm on a small population (30 people) in India in order to see what we have not accounted for before. After adjusting our sensors and algorithm accordingly, we would ideally run a large test in India during a heat wave -- the frequency of heat stroke is small enough (~0.0005%) that a large sample size of at least 1,000,000 people would be needed to have a decent chance of having a user with heat stroke.

---

[2] Buller MJ et al. "Estimation of human core temperature from sequential heart rate observations." Physiol Meas. 2013 Jul;34(7):781-98. doi: 10.1088/0967-3334/34/7/781. Epub 2013 Jun 19.

- We could then calculate the sensitivity, specificity, and accuracy of our algorithm.

**4.5: Supporting Material/Appendices**

**Appendix A (Github):** Integrated code for prediction algorithm.

**Appendix B**: Video of running prediction algorithm when Jon wore our device in the Heller Lab (2/28/17).

**Appendix C: Heller Lab nonexertional heat stress protocol,** as follows:
- Make sure Bean+ is fully charged
- Insert esophageal temperature probe through nose
- Strap heart rate monitor around chest
- Turn Bean+ on
- Wrap delicate electronics of Bean+ sensor system in saran wrap, then hold Bean+ in one hand
- Put on hazmat suit, mask to cover head and face, and tie garbage bags around hands
- Sit in 46°C room until core temperature reaches 39°C (below heat stroke)
  - Heller Lab equipment is recording heart rate and esophageal (core) temperature
  - Laptop is reading sensor data from outside the room and making predictions

**Appendix D: Shriram 112 non-exertional protocol,** as follows:
- Bean+ should either be fully charged or plugged into laptop to charge
- Turn Bean+ on
- Place sensors (pulse monitor, GSR) on fingers
- Start prediction algorithm
- Sit for 45 minutes

**Appendix E: Shriram 112 exertional protocol,** as follows:
- Same as Appendix C, but instead of sitting for 45 minutes, do exercises in place (jumping jacks, fast feet, dancing, etc.) for 10 minutes

**E.1: Plots from Shriram 112 exertional protocol (10 min):**

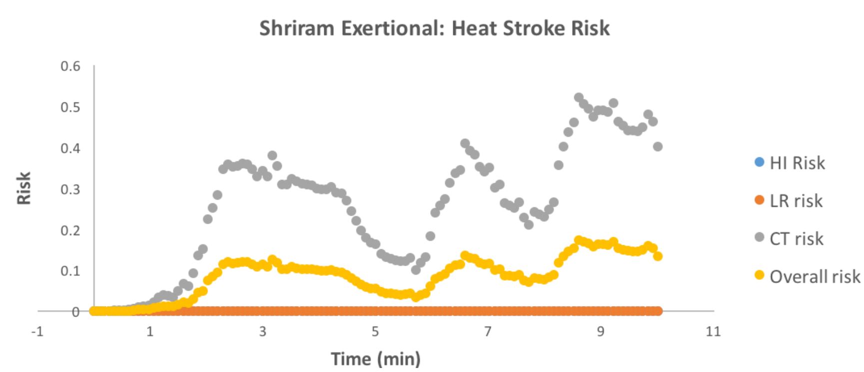


**Figure E.1: Plot of Shriram 112 exertional heat stroke risk (0-1 scale) using various models over time.** HI = heat index; LR = logistic regression; CT = core temperature (estimate based on heart rate).

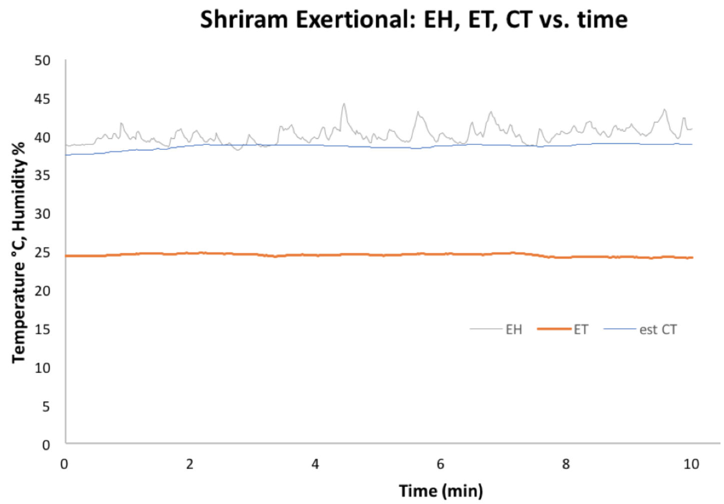


**Figure E.2: Plot of Shriram 112 exertional ET, EH, and CT vs. time.** ET shown in orange, CT shown in blue, EH shown in gray. ET remains constant for the duration of the 10-minute test, EH fluctuates (potentially due to local changes from body heat/sweat from holding the Bean+), and estimated CT rises from 37.6°C to 38.9°C.

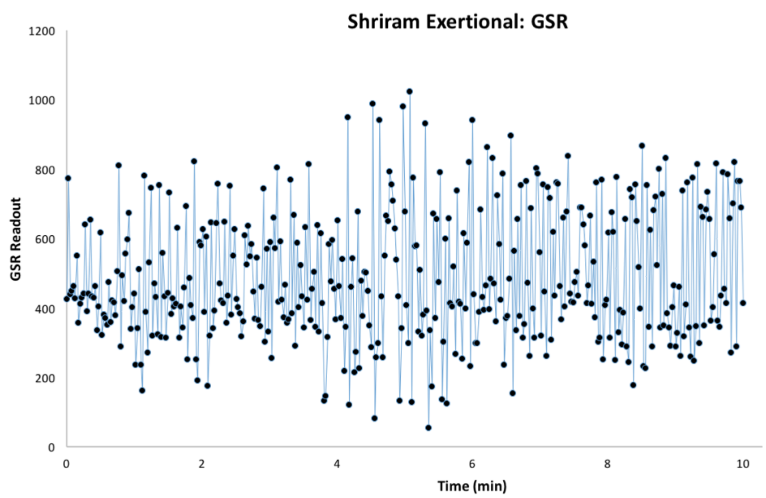


**Figure E.3: Plot of Shriram exertional GSR sensor data.** Each measurement taken ~0.025 min (1.5 seconds) apart. Data appear to be very noisy with no real discernible trend.

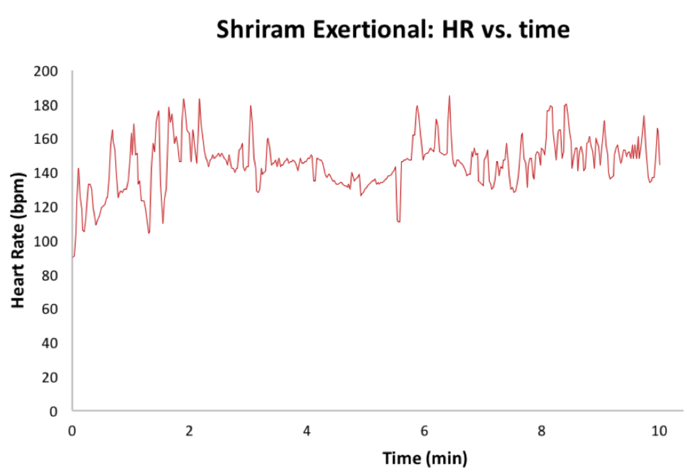

**Figure E.4: Plot of Shriram exertional HR vs. time.** Measurements taken with pulse monitor sensor while Anna did jumping jacks, fast feet, moving around in one general area, etc. For future testing, it would likely be more ideal to rest for a period of time before beginning activity (rather than right away) in order to better show heart rate increase as a result of exercise.

**Appendix F.1: Testing GSR without fingers in the sensor.**

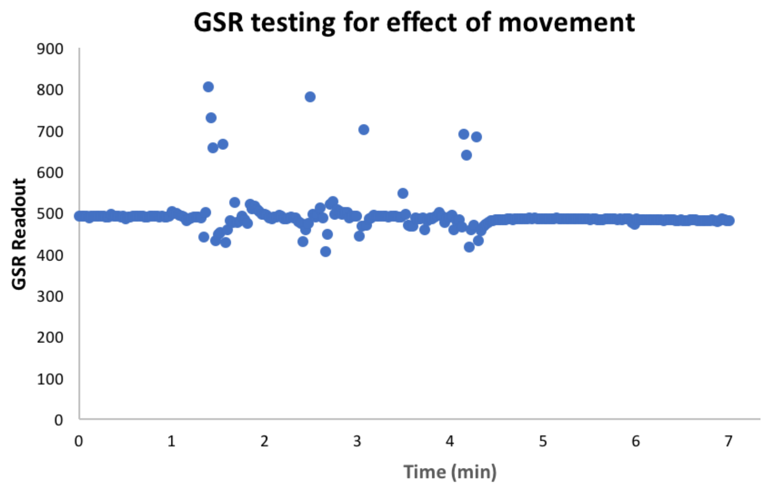


**Figure F.1: Plot of GSR (without fingers in sensor) over time.** Bean+ and GSR sensor were left on a table and then picked up and moved around at ~1.5 min, ~2.5 min, ~3.5 min, and ~4 min. Movement appears to skew GSR values in both directions, resulting in some that are high outliers.