ECE 445

Senior Design Laboratory

Project Proposal

STORM: **S**print **T**raining **O**ptimization and **R**eal-time **M**onitoring

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1 Introduction

1.1 Problem

In most sprint and distance running training, there is a significant lack of accessible tools for monitoring key biomechanical and biometric metrics. Metrics such as ground contact time, stride cadence, thigh angular velocity, heart rate, and VO2 max are critical to optimizing an athlete's performance, particularly in short-distance sprints like the 100m. However, current solutions, including force-sensing treadmills, motion analysis systems, and coaching, are expensive and inaccessible to most athletes. This is because these tools are usually only found in specialized gyms, hindering athletes' ability to make immediate adjustments to their form and training intensity when training alone.

Additionally, existing fitness wearables are typically designed for long-distance runners and only track general data like speed and heart rate averages, which are not applicable to short-distance sprints. They also do not provide the detailed biomechanical analysis necessary for improving running form during both sprints and distance running. For example, thigh angular velocity and ground contact time, which are the most impactful metrics on running speed, remain untracked by most commercially available devices. These wearables also lack visualization systems for such data, which are essential for athletes aiming to learn about ther performance and optimize their sprinting form and efficiency through training adjustments.

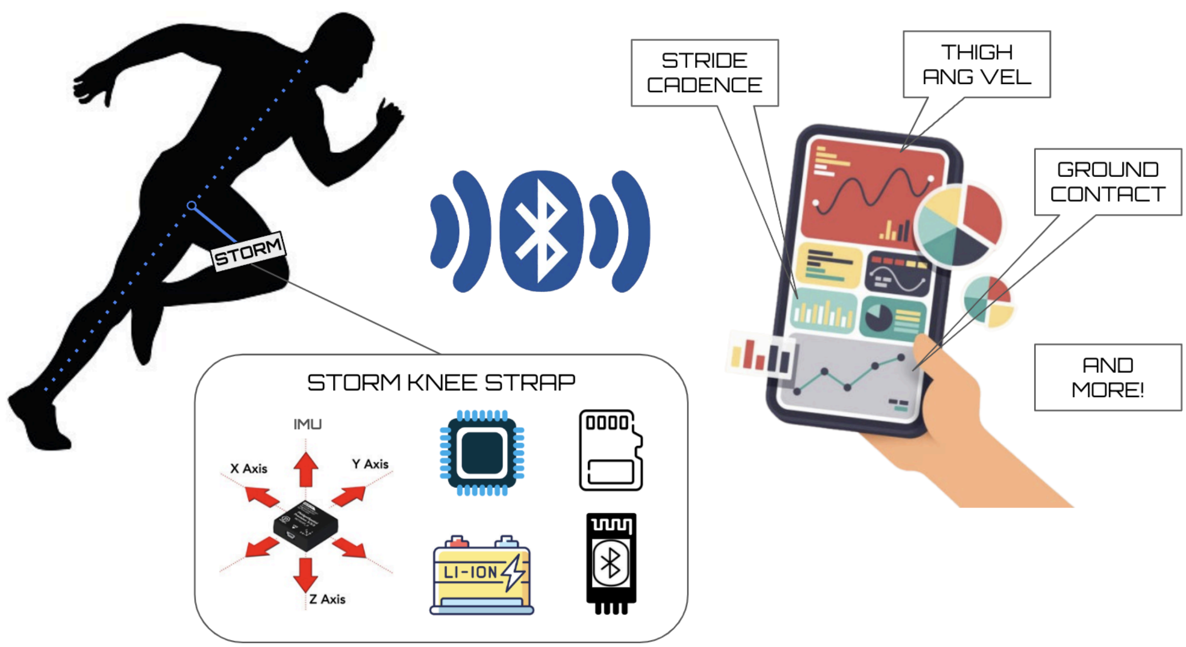
There is a clear need for a more affordable, comprehensive system that can track both biomechanical and biometric data in real-time, providing actionable insights that help athletes improve sprint technique and performance.

1.2 Solution

Our primary solution, or Minimum Viable Product (MVP), is a knee strap monitoring system paired with a mobile app designed to track and analyze both sprint and distance running form and technical performance. The knee strap includes a gyroscope, accelerometer, power circuitry, microcontroller, and memory system, allowing it to capture essential biomechanical data such as stride cadence, ground contact time, and thigh angular velocity during runs. This data is wirelessly transmitted to the mobile app, where athletes can visualize their performance metrics in real-time and gain actionable insights to improve their running technique. Whether for sprints or longer distances, this system directly addresses the gap in affordable, accessible tools for optimizing running performance from a technical perspective.

As for the stretch goal (above the scope of the main project), we propose introducing an additional chest strap system to further enhance the solution's capabilities. The chest strap will track additional metrics such as overall body position, overall speed, and heart rate, and will include a haptic feedback motor to notify athletes when their heart rate has dropped to a level indicating full recovery between efforts. While the knee strap and app alone provide a comprehensive solution to the core problem of improving running form and technical performance, the chest strap adds value by offering insights into cardiovascular performance and recovery, particularly for distance runners and those focused on conditioning.

1.3 Visual Aid



1.4 High-Level Requirements

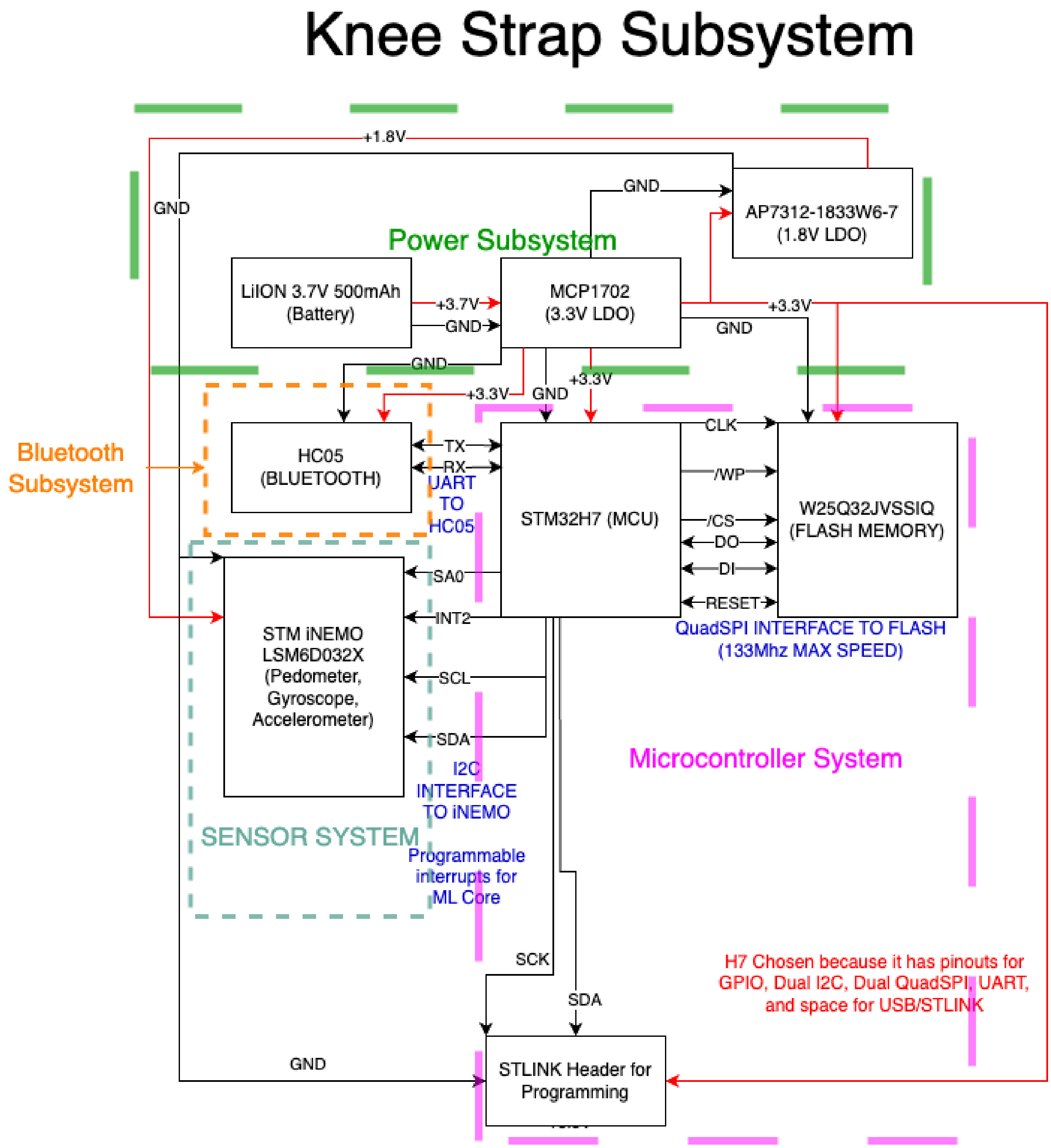
1. Accuracy and Precision of Biomechanical Measurements:
    - Requirement: The subsystems shall have a measurement accuracy within a 10% margin of error for the biomechanical metrics of ground contact time, stride cadence, and thigh angular velocity in comparison to high-speed video analysis.
    - Justification: This ensures that the sensor provides reliable and accurate data, which is crucial to assess performance effectively.
2. System Reliability and Environmental Durability:

- Requirement: The system will withstand typical environmental conditions that occur while training a sprint, such as impacts, moisture (sweat resistant), and temperature fluctuations between 30℉ and 120℉ without any loss of performance for at least 90 minutes.
- Justification: Ensures that the device is robust and would be suitable for continuous athletic use in realistic climatic conditions.

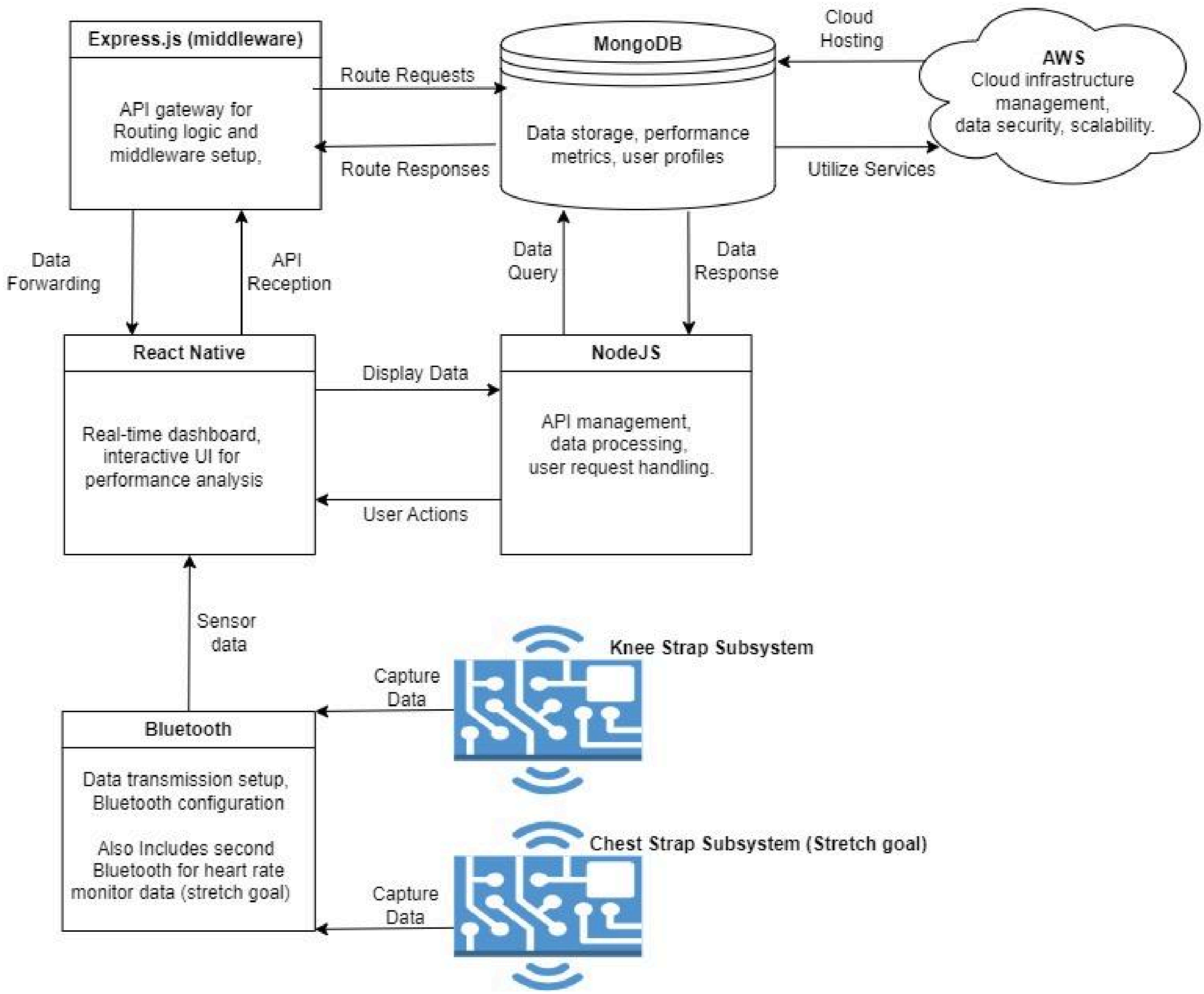
3. Data Collection and Bluetooth Transmission:
    - Requirement: The subsystems will collect and write biomechanical data to its flash memory at a rate of 10 data points per second, ensuring that data is recorded within 0.1 seconds per measurement. Once all data is collected, athletes can press the "Load Data" button on the mobile app, which will initiate the Bluetooth transmission, and complete data transfer must take less than 5 seconds.
    - Justification: The data must be collected at least 10 times per second to create detailed, useful data about sprint form, and efficient transmission of data allows for the user to quickly see results at the end of their workout.
4. App Performance and Usability:
    - Requirement: The mobile app will present sprint data in a user-friendly UI that displays real-time metrics with no more than a 5-second delay. The app must provide a clear, intuitive display of performance metrics, including progress over multiple training sessions spanning at least 3 months. It will generate updated AI-driven training recommendations within 1 minute of receiving new workout data. Of course, app usability and user-friendliness are subjective measures, but we will try our best to deliver an objectively high quality app.
    - Justification: The app must be intuitive and responsive, ensuring that athletes can quickly interpret their performance metrics without delay. The ability to track progress over time is critical for long-term improvement, and AI-generated recommendations will provide personalized training guidance.

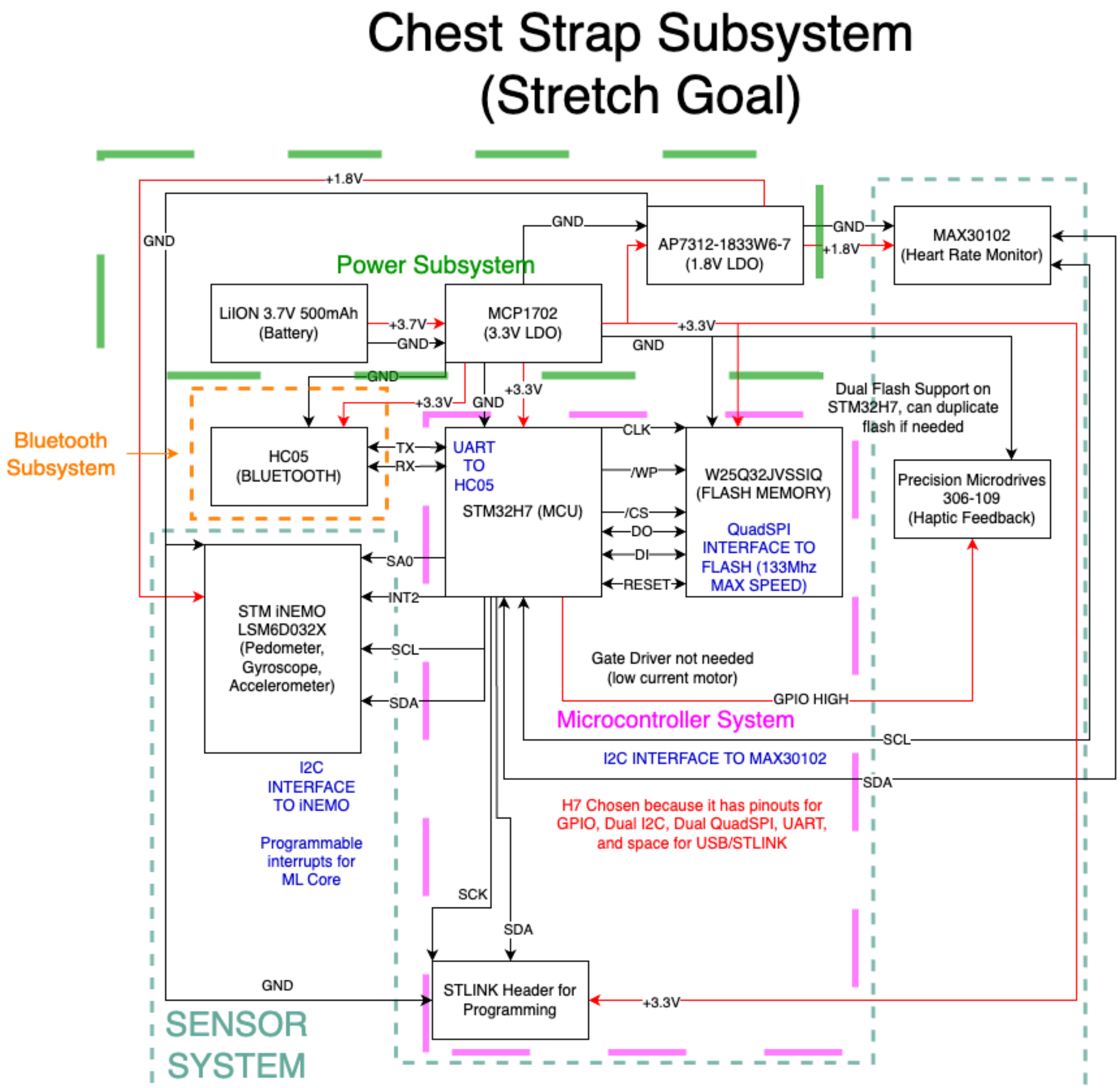
2 Design

2.1 Block Diagrams



Mobile App Subsystem





2.2 Subsystem Overview and Block Descriptions

2.2.1 Knee-Strap Subsystem

The knee strap subsystem is the physical component of the MVP of the project. It consists of the microcontroller system (which contains an STM32H7, W25Q32J Flash, and STLINK programming header), the power subsystem (Lithium Ion cell, 3.3V LDO, and 1.8V LDO), the Bluetooth subsystem (HC05 Bluetooth module), and the sensor subsystem (STM32 iNEMO Inertial measurement unit). The STLINK was chosen to avoid the bulk of a traditional JTAG debug connector, and the iNEMO inertial unit was chosen to combine the accelerometer and gyroscope into a single package, reducing latency and helping to bring the system close to real time analysis. The STM32H7 communicates with the Flash memory over QuadSPI, and uses I2C for the iNEMO accelerometer unit. We utilize I2C to communicate with the iNEMO to take advantage of the ML Core and preprocessing hardware available in the sensor module. Bluetooth communication happens over UART, as that is a hardware limitation of the HC-05 Module.

2.2.2 Mobile App Subsystem

The mobile app processes data from the sensor subsystems and displays it to the user in an intuitive, technical layout. Our app will be built using a MERN stack with AWS backend infrastructure and Bluetooth connectivity. First, the data is retrieved from the sensor subsystems through Bluetooth and preprocessed by the NodeJS backend. This data is then sent to the AWS Cloud for further processing using AWS cloud services, Python functions, and ML analysis. Then, this processed data is stored in a MongoDB database and relevant data is sent back to the mobile app, where the data is presented to the user in our intuitive, user-friendly React Native frontend. All of the communication between the frontend and backend is done through our Express API gateway for efficient communication. While using the app, the athlete can view detailed, technical graphs and time-series data related to their training and performance. The mobile application will also offer AI-driven recommendations on training adjustments and long-term graphs for tracked performance and improvements over multiple training sessions, in addition to more granular, intra-session analysis.

2.2.3 Chest-Strap Subsystem (Stretch Goal)

The chest strap subsystem is the stretch goal of the project. To be clear, this subsystem functions independently of the knee-strap subsystem. It consists of the microcontroller system (which contains an STM32H7, W25Q32J Flash, and STLINK programming header), the power subsystem (Lithium Ion cell, 3.3V LDO, and 1.8V LDO), the Bluetooth subsystem (HC05 Bluetooth module), and the sensor subsystem (STM32 iNEMO Inertial measurement unit, MAX30102 Heart rate sensor, and a haptic motor). The STLINK was chosen to avoid the bulk of a traditional JTAG debug connector, and the iNEMO inertial unit was chosen to combine the accelerometer and gyroscope into a single package, reducing latency and helping to bring the system close to real time analysis.The STM32H7 communicates with the Flash memory over QuadSPI, and uses I2C for the iNEMO accelerometer unit. We utilize I2C to communicate with the iNEMO to take advantage of the ML Core and preprocessing hardware available in the sensor module. Bluetooth communication happens over UART, as that is a hardware limitation of the HC-05 Module. The heart rate sensor is also connected to the STM32 over I2C, and the haptic motor driver is driven directly from the GPIO pin. We did not use a gate driver in our design because the motor is extremely low current and can be driven directly from the GPIO pinout of the STM32H7 (which was chosen to take advantage of multiple communication protocols and the higher current output). The additional heart rate sensor and haptic motor are used to monitor biometrics and provide feedback to the user on heart rate based recovery timing and confirmation of data transfer from the onboard system to the bluetooth mobile app.

2.3 Subsystem Requirements

2.3.1 Knee-Strap Subsystem

The knee strap subsystem is responsible for capturing and processing biomechanical data during sprints. It includes sensors that monitor key leg-movement specific metrics, ensuring both accuracy and durability in typical training conditions. Data collection and transmission will be handled efficiently, allowing athletes to review performance metrics promptly post-workout.

Subsystem	Requirements
Power: Without stable power, none of the components would function reliably, causing the system to fail.	● The 3.3V LDO must provide at least 500 mA of current, ensuring reliable operation of the microcontroller and Bluetooth module. ● The 1.8V LDO must supply at least 150 mA with similar voltage tolerance to avoid sensor inaccuracies. ● The battery must support at least 2 hours of continuous operation, with a capacity of at least 500 mAh to power all subsystems during a typical running session.
Microcontroller: the MCU controls the operation of the knee strap subsystem.	● The STM32H7 must run at least 200 MHz to make sure it is processing near real-time data. ● The microcontroller must be able to handle SPI/I2C communication at high speeds (at least 10 MHz for SPI) to avoid bottlenecks during sensor data acquisition.
Bluetooth: Without Bluetooth connectivity, the system would fail to communicate with the app.	● The Bluetooth module must maintain a transmission range of at least 5 meters to ensure data can be transferred from the knee strap to the mobile phone when requested. ● The Bluetooth module must be able to handle continuous data transmission at a rate of at least 20 kB/s to ensure efficient transfer.

Sensor: Removing or downgrading the sensor subsystem would result in the inability to measure critical metrics.	● The IMU must be able to measure accelerations up to ±16g and angular velocity up to ±1000°/s to capture the full range of running movements, from sprints to slower jogs. ● The IMU must have a sampling rate of at least 100 Hz to ensure real-time data collection.

2.3.2 Mobile App Subsystem

The mobile app subsystem is used to interface between the athlete and the biomechanical data collected by the knee strap subsystem. It will present the collected sprint metrics in a clear, user-friendly format and provide insights on performance, progress tracking, and AI-driven training recommendations. The app will ensure that data is processed and displayed with minimal delay, while allowing users to view their progress over multiple training sessions. Additionally, it will enable efficient data transmission from the knee strap and offer personalized training recommendations based on user statistics.

Subsystem	Requirements
Bluetooth API: Without a functioning Bluetooth connection, no sensor data would be available for analysis, causing the entire app to fail in its primary function.	● The Bluetooth API must support data transmission at a minimum rate of 20 kB/s to avoid delays.
Cloud and Data Storage: Without proper cloud synchronization, users would not benefit from advanced processing and machine learning insights, reducing the value of the app.	● The mobile app must be able to sync data with AWS at least every 5 minutes during training sessions to ensure no data loss. ● MongoDB should handle at least 100MB of local storage, enabling users to store multiple training sessions without immediate cloud sync. ● AWS services must handle processing and storing up to 100 MB of biomechanical data per session.

Frontend: Without a properly functioning visualization subsystem, users would be unable to interpret their performance data, negating the purpose of the app.	● The data visualization subsystem must render performance metrics in under 5 seconds to provide a smooth user experience. ● The app must display time-series graphs with a minimum resolution of 10 data points per second to ensure detailed tracking of performance changes. ● The interface must be simple and intuitive.
AI Analysis: Without AI recommendations, users would lose the ability to improve performance based on data-driven training insights.	● The AI subsystem must process biomechanical data and generate recommendations within 1 minute of the session's conclusion. ● The machine learning models must deliver accurate recommendations and insights based on the latest technical sprint literature. This requirement will be verified subjectively by our team, using our educated judgment and domain knowledge.

2.3.3 Chest-Strap Subsystem (Stretch Goal)

The chest strap subsystem is nearly identical to the knee strap because it captures and processes biomechanical data during sprints, along with the added functionality of monitoring cardiovascular metrics and providing haptic feedback. In addition to the IMU used to track metrics like overall body position and speed, the chest strap includes heart rate sensors to offer insights into cardiovascular performance. A haptic feedback motor is incorporated to notify athletes when their heart rate drops to a level indicating full recovery between efforts, enabling more efficient training sessions.

Subsystem	Requirements
Sensor: Removing or downgrading the sensor subsystem would result in the inability to measure critical metrics.	● The IMU must be able to measure accelerations up to ±16g and angular velocity up to ±1000°/s to capture the full range of running movements, from sprints to slower jogs. ● The IMU must have a sampling rate of at least 100 Hz to ensure real-time data collection.

	• The heart rate sensor must be able to measure heart rates from 30 BPM to 220 BPM with an accuracy of ±4 BPM to cover all phases of training. This will be verified by comparison with industry standards like the Apple Watch. • The heart rate sensor must sample at a minimum rate of 1 Hz to provide near real-time feedback on heart rate changes during and after exercise. • The haptic feedback motor must be capable of generating tactile signals that are strong enough to be felt through typical training clothing layers. This will be verified by in-field testing by our team. • The haptic motor must be able to deliver feedback within 2 seconds of receiving the signal to ensure prompt notification when the athlete's heart rate drops to the desired recovery level.
All other subsystems	See 2.3.1

2.4 Tolerance Analysis

Our project shows multiple tolerance issues. The three we are choosing to address are given below:

1. We will need to account for the IMU component overestimating or underestimating strides due to the difference in the user's heights and motion states.
2. We will need to account for the knee subsystem to overdraw the current from the onboard linear regulator (MCP1702 3.3V) causing it to overheat.
3. We will need to account for the lack of precise start and end times for the sprint by adjusting for drift velocities.

2.4.1 Inaccuracy in Step Length For Different User Heights and Motion States

To have the most effective athletic training monitoring, we will need to ensure the accuracy of the step lengths have the least variance as possible. We employ the following model to estimate step length and compare the iNEMO's values:

$$S_{Li} = h \cdot (A \cdot f_i + B \cdot var_i + C) + D$$

In this equation, SL_i represents the step length for the ith step, h represents the user's height, f_i is the stride frequency, and var_i is the vertical acceleration variance. To calculate for f_i, the stride frequency, we can incorporate the equation:

$$f_i = \frac{1}{t_i - t_{i-1}}$$

In this equation, t_i and t_{i-1} represent the corresponding times between two adjacently detected steps. To calculate for var_i, the stride frequency, we can incorporate the equation:

$$var_i = \frac{1}{N-1} \sum_{t=t_i - 1}^{t_i} (a_t - a_i)^2$$

In this equation, a_t represents the acceleration at time t, and a_i represents the average acceleration. N in this example is the number of samples taken during the step. This variance helps in understanding the consistency for each step. The coefficients *A, B, and C* are determined using the least squares method (minimizes the sum of the squared deviations between observed and predicted step lengths).

2.4.2 Overheating from Excessive Power Draw

One of the biggest concerns in this project is safety, specifically of overheating components, which could occur with the voltage regulator (MCP1702 and AP7312) and thus we would need to account for its prevention. The table below shows the potential current drawn from each of our components and the potential thermal impact it can have:

Component	Typical Current Draw
STM32H7	200 mA
HC05 Bluetooth Module	3 mA
STM iNEMO LSM6D032X	0.38 mA
Flash Memory: W25Q32JVSSIQ TR	28 mA

We are using 2 voltage regulators for this project. The MCP1702 3.3V and the AP7312 1.8 V. The STM iNEMO will connect to the AP7312 while the other components will connect to the MCP1702. These MCP1702 and AP7312 will have the following ratings respectively:

MCP1702:

Property	Values
Absolute Maximum output current	500 mA
Absolute Maximum operating temperature	150℃
Maximum Thermal resistance per Package	336℃/W

AP7312:

Property	Values
Maximum output current	300 mA
Maximum operating temperature	150℃
Thermal resistance	140℃/W

We utilize the MCP1702 voltage regulator with a thermal resistance of *125°C/W* and a maximum junction temperature of *150°C.* The maximum power dissipation is calculated using:

$$P_{MPC1702}=(V_{in}-V_{out})\cdot I=(5V-3.3V)\cdot 0.250A\approx 0.425W$$

$$P_{\mathrm{AP7312}}=(V_{in}-V_{out})\cdot I=(5V-1.8V)\cdot 0.300A\approx 0.960W$$

This yields an estimated theoretical maximum temperature of:

$$Tmax=P_{MPC1702}\cdot R_{thermal\text{-}max}=0.425W\cdot 336°C/W=142.8°C$$

$$Tmax=P_{\mathrm{AP7312}}\cdot R_{thermal}=0.960W\cdot 140°C/W=134.4°C$$

Keep in mind these maximum temperature ratings are based on the theoretical absolute maximum output values from the LDO. Since our design will never actually pull 250mA of current from the LDO, nor will it operate at the maximum junction temperature (ambient knee is approximately 36℃), nor will the thermal package resistance be 336℃/W (we are not using a four-layer PCB), there should be no risk of reaching 142.8℃, or 134.4℃. Overall there should be stable operation with our project without the need for worrying about overheating.

2.4.3 Precise Detection of the Start and End of a Sprint

It is vital for sprinters to have the exact start and end time for a sprint without worrying about potential offsets. These inaccuracies due to either the sensor delay or potential noise could cause overall inaccuracies in our analysis. We resolve this with double integration for acceleration calculations (from acceleration to velocity and finally displacement) and accounting for drift velocities to decipher from the sprint and the sprinter simply adjusting or moving themselves.

In addition, the drift during a moving period is calculated as the difference between the velocity estimates at the end and the start of that period. This is given by:

$$Drift\ rate = \frac{Ve - Vb}{e-b}$$

Here, V_e and V_b represent the velocities at the end and beginning of the movement, while e and b denote the respective times of these velocity measurements. Each velocity sample within the period is adjusted to remove the calculated drift, which reflects the true movement more accurately.

$$V_{corrected} = v_{ti} - drift\ rate \times (t_i - t_b)$$

3 Ethics and Safety

For us to maintain the ethical and safety code of conduct, we are pledging to the IEEE code of ethics while building this sprint optimization system, and specifically section III where it states: “We will avoid injuring others, their property, data, reputation, or employment by false or malicious action”.

3.1 Ethical Concerns

3.1.1 Transparency of Algorithmic Decisions

With STORM, we ensure that the algorithm used for the sprinter performance and recommendations to better their sprints are transparent and understandable. This is vital for athletes and even coaches to understand how the decisions are made by our system. Ensuring that these algorithms don’t create biases or favor specific demographics (mainly height), is critical to maintaining the ethical deployment of our technology.

3.2 Safety

We commit to adhering to specific industry standards and regulatory guidelines to uphold the highest standards of safety in the development and deployment of Project STORM,

3.2.1 Compliance with Sports Equipment Standards

ASTM Standards for Sports Equipment: Project STORM will adhere to ASTM standards, such as ASTM F2276-10(2019), which provides the standard specification for fitness equipment and its safety and performance requirements. This ensures that all hardware components used in our monitoring system are safe, reliable, and pose no risk to the users.

3.2.2 Safety Concerns

Our primary safety concerns involve ensuring the physical security and reliability of the sensor systems used in STORM:

To eliminate the risks associated with electronic failures, which could include overheating of components or battery malfunctions mainly, our design will conform to the IEC 60068 series on Environmental Testing for electronics. This series provides guidelines on how to assess the durability and operational safety of electronic components under various environmental conditions.

4 References

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[5] “Standard specification for fitness equipment,” F2276, https://www.astm.org/f2276-10r15.html (accessed Sep. 19, 2024).