

**ReActive Comfort: Enhancing Ankle Support Through Pressure Adaption**

**Grant Proposal**

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### Executive Summary

Ankle injuries are among the most common musculoskeletal injuries worldwide, particularly for athletes and individuals with active lifestyles. While traditional ankle braces are effective at limiting excessive joint motion, they rely on constant compression levels that fail to adapt to changing movement demands. This static support often leads to discomfort and reduced compliance, causing users to remove their braces prematurely and increasing the risk of re-injury. Current research highlights that comfort and adaptability are the strongest predictors of brace adherence. Yet affordable, wearable ankle braces capable of real-time adaption remain largely unavailable outside of experimentation.

This proposal introduces ReActive Comfort, a pressure-responsive adaptive ankle brace designed to dynamically adjust internal tension in response to real-time force. Using force-sensing resistors (FSRs), a microcontroller-based control system, and a motorized tightening mechanism, the brace increases stabilization during high-intensity movements and relaxes during low-load activity to maintain comfort. The project pursues three specific aims: (1) designing and calibrating a sensor-driven adaptive brace prototype, (2) developing a rapid-response control system capable of adjusting tension in under two seconds, and (3) evaluating mechanical performance and comfort relative to a standard nonadaptive brace using bench and simulated inversion testing. By combining affordable hardware with intelligent control and reinforcement learning, this project bridges the gap between rigid protective devices and passive compression sleeves. Successful completion will establish a scalable framework for adaptive orthopedic supports and lay the foundation for future applications to other joints, advancing injury prevention, rehabilitation, and long-term musculoskeletal health.

*Keywords:* Adaptive ankle brace, Pressure-responsive support, Injury prevention, Biomechanics

## ReActive Comfort: Enhancing Ankle Support Through Pressure Adaption

Ankle injuries represent one of the most prevalent musculoskeletal issues worldwide, particularly among athletes and individuals with active lifestyles. Traditional ankle braces, though effective at stabilizing the joint, are often designed with constant compression level, which does not account for variations in movement or load. This uniform pressure can cause discomfort, irritation, and reduced wear time, ultimately compromising recovery and long-term stability. As a result, many users remove their braces prematurely or fail to wear them as prescribed, reducing treatment effectiveness and increasing the likelihood of re-injury.

### Importance of Ankle Stability

Research demonstrates that maintaining constant ankle stability is critical for balance and lower limb coordination. Crenna and Frigo (2011) examined ankle joint mechanics in 120 healthy adults and found that the torque-angle relationship of the ankle remains biomechanically stable across adulthood, supporting the joint's key role in locomotion. However, when external support fails to adapt to changes in activity, they can interfere with this natural control, emphasizing the need for a brace that both supports and adjusts dynamically to maintain biomechanical harmony.

**Previous Research and Limitations.** The current market offers a wide range of braces, from semi-rigid stabilizers to flexible compression sleeves, but none offer real-time adaptability. Janssen (2016) found that user comfort and brace preference vary significantly depending on the sport and perceived stability, showing that comfort, not rigidity, most strongly predicts compliance. More recent studies, such as those by Megalaa et al. (2024) and Willwacher et al. (2023), have explored adaptive brace technologies that adjust stiffness based on movement. Their results confirm that adaptive systems improve comfort and perceived safety compared to static models. However, most of these innovations remain in laboratory testing, relying on complex or expensive materials. There is a clear gap in

affordable, wearable adaptive ankle supports that respond to real-time pressure while maintaining comfort and functionality for everyday users.

To address this limitation, this project proposes to design and test a pressure-responsive adaptive ankle brace that automatically adjusts internal tension in response to varying activity levels. The device will utilize force sensing resistors (FSRs) to detect changes in applied pressure and communicate with a microcontroller, which will tighten or loosen internal straps within seconds. This system is designed to maintain both comfort and stability throughout a full range of movement, creating a personalized level of support for each user.

## **Section II: Specific Aims**

### **Overall Objective**

This proposal's objective is to design and test an adaptive ankle brace capable of responding to the amount of pressure placed on the limb in real time. As activity intensity increases, the brace will automatically tighten to provide greater stabilization, and as intensity decreases, it will loosen and reduce discomfort to maintain circulation.

### **Long-Term Goal**

The long-term goal is to develop a line of adaptive orthopedic supports that enhance mobility and comfort for both athletes and general users. The central hypothesis of this proposal is that a brace integrating pressure feedback with automated mechanical adjustment will increase user comfort and compliance without reducing stabilization. The rationale is that improved comfort and adaptability will lead to longer wear times and better recovery outcomes, especially for individuals with chronic ankle instability (CAI) or those returning from acute injury.

### **Specific Aims**

**Specific Aim 1:** Design a functional adaptive ankle brace prototype that uses FSR sensors to monitor pressure during movement.

**Specific Aim 2:** Develop a responsive control system that adjusts internal brace tension in under 2 seconds based on force readings.

**Specific Aim 3:** Evaluate mechanical performance and user comfort compared to a standard brace through bench and simulated trials.

### **Expected Outcomes**

The expected outcome of this work is a validated prototype that demonstrates automatic, real-time pressure response, improved user comfort, and consistent mechanical performance. If successful, this system will lay the groundwork for future adaptive support technologies that use similar sensing and feedback systems for other joints such as the knee, wrist, or elbow.

## **Section III: Project Goals and Methodology**

### **Relevance/Significance**

**Need for Adaptable Support in Athletics:** Ankle instability can lead to reduced mobility, chronic discomfort, and an increased risk of further injury. Alwana and Mohamad (2020) showed that interventions like taping and proprioceptive training can improve balance and performance for athletes with chronic ankle instability, but these solutions lose effectiveness over time or require continued supervision. Similarly, Cain et al. (2020) found that common rehabilitation methods like resistance band or balance board exercises yield improvement but depend on consistent user adherence. These findings underscore the need for autonomous mechanical solutions that provide ongoing stabilization and adapt to activity without user input.

The proposed adaptive ankle brace offers a mechanical equivalent to supervised rehabilitation, one that adjusts automatically as activity intensity changes. It bridges the gap between rigid braces that prioritize protection and elastic sleeves that prioritize comfort by combining smart sensing with

responsive tension control. The technology leverages affordable, widely available components: FSR sensors to measure distributed load, an Arduino-based microcontroller for processing and an adjustable elastic or servo-driven tension mechanism. Together, these components create a closed-loop system that maintains optimal pressure in real time.

### **Innovation**

This project's innovation lies not only in the use of adaptive sensing but also in its feasibility and accessibility. Commercial smart footwear systems, like Moticon or Digitsole, can collect biomechanical data but do not provide mechanical feedback or adaptive support. These systems cost hundreds of dollars, while the proposed brace can be developed for under \$100, making it accessible for everyday consumers, physical therapy patients, and sports programs.

In addition, this project aligns with broader research on wearable biomechanics and assistive technology, demonstrating how simple, low-cost materials can produce meaningful advancements in rehabilitation and injury prevention. The successful development of this prototype could inspire future collaborations between engineering, sports medicine, and rehabilitation science to enhance comfort, performance, and long-term musculoskeletal health.

### **Methodology**

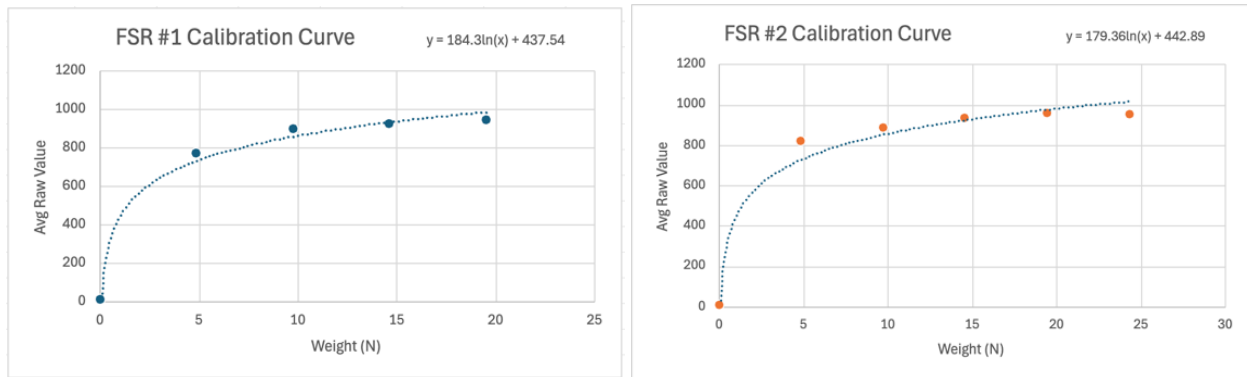
#### ***Specific Aim #1:***

The objective of this aim is to determine the optimal placement of force-sensing resistors (FSRs) and actuators on an ankle brace to create an initial pressure-response control model. A commercially available lace-up brace will serve as the first testing platform because it allows quick modification and provides a realistic structure for early trials. After FSR calibration, various sensor placements will be evaluated to determine which positions produce clean, repeatable pressure readings during simulated

measurements. This data will be used to create the first version of a system that determines how much the brace should tighten or loosen under different pressure levels. Early development on an existing brace reduces design constraints and helps define mechanical requirements before transitioning to a custom model.

**Justification and Feasibility.** Accurate sensor placement is essential for developing a reliable response system because pressure around the ankle shifts quickly during movement. Razak et al. (2012) showed that plantar pressure sensors are highly sensitive to placement and small position changes can significantly alter data quality. Their findings support the need to test multiple FSR locations before selecting final positions. The feasibility of using FSRs in a wearable brace is reinforced by Crea et al. (2014), who demonstrated that flexible, low profile FSRs remain stable and responsive even when curved or compressed during gait analysis. Wright et al. (2000) further reported that the ankle experiences its highest loads along the lateral side during inversion-prone foot positions, identifying predictable regions where sensors are most likely to detect meaningful pressure changes. Together, these studies justify early trials on a lace-up brace and confirm that creating a calibrated, placement-specific pressure-response system is realistic and achievable.

**Summary of Preliminary Data.** Calibration testing was conducted for two FSRs to confirm that they provide reliable, interpretable pressure measurements before evaluating placement on the ankle brace. As shown in Figure 1 and Figure 2, both sensors produced the expected nonlinear increase in output with higher loads, and each fit well to a logarithmic trendline.



**Figures 1 & 2 (left to right):** Calibration curves for Force Sensitive Resistors (FSR's) 1 and 2 with corresponding equations.

The two calibration equations as shown in the figures were within the same range, indicating consistent behavior across similar sensors.

Both curves demonstrated clear sensitivity at low forces and stable response across the loading range relevant to the ankle, confirming that the sensors are functioning properly. These results provide the necessary baseline to convert raw readings to force estimates and support the feasibility for testing multiple placement locations.

**Expected Outcomes.** The overall outcome of this aim is to create a finalized sensor and actuator placement map and a basic pressure response model that connects measured force to specific tightening or loosening actions. These results will inform the custom CAD design in Specific Aim 2 and provide structured labeled data necessary for later machine learning and reinforcement learning components.

**Potential Pitfalls and Alternative Strategies.** Possible challenges include inconsistent readings caused by sensor shifting, uneven pressure caused by motor placement, or interference from the structure of the lace of brace when the motors are moving. If signal noise occurs, filtering techniques

such as smoothing or low-pass filtering will be added. If actuator placement creates discomfort or uneven tension, alternative mechanisms, such as cable routing or compliant actuators, may be substituted. If initial brace structure limits performance of the motors, the project will move earlier into CAD-based prototyping to eliminate structural constraints.

***Specific Aim #2:***

This aim focuses on developing a custom CAD designed ankle brace and creating a predictive machine learning model that can anticipate pressure changes based on simulated movement patterns.

Information gathered during the first iteration will be used to design a less-rigid structure that strays away from the commercial lace-up brace. It will incorporate built-in channels for sensors, wiring, and the motorized tightening mechanism. A simulation environment will then be created to mimic realistic ankle-movement patterns such as walking, jogging, or lateral motion. Data generated from the simulation will be used to train a reinforcement-learning model capable of forecasting pressure changes before they occur, improving the responsiveness of the adaptive system.

**Justification and Feasibility.** Current ankle braces are largely passive and provide constant levels of support, which can reduce comfort and limit user compliance. Research by Park et al. (2021) demonstrates the feasibility of using 3D-printed honeycomb metamaterials with non-linear, strain stiffening behavior to create a flexible yet supportive adaptive ankle brace. This validates the approach of designing a less rigid structure that can accommodate actuators, wiring, and embedded sensors while maintaining sufficient structural integrity. Additionally, the work by Choffin et al. (2021) shows that a set of FSRs embedded in a flexible substrate combined with a microcontroller and a machine learning algorithm can predict ankle joint angles with high accuracy. This provides strong proof of concept for using FSR-based pressure data to anticipate pressure and joint behavior.

**Expected Outcomes.** This aim is expected to produce a functional CAD-based brace prototype, the second iteration, with integrated sensor and actuator placement. In addition, the simulation is expected to gather data around different pressure levels, activities, and ankle angles that cannot be tested in real life due to the scope of this project.

**Potential Pitfalls and Alternative Strategies.** Potential issues include limited predictive accuracy, unrealistic simulation, or structural weaknesses in the CAD design. If simulation data lacks realism, domain-randomization techniques or hybrid datasets may be used. Mechanical issues in the CAD model may be addressed through the use of TPU, EVA, or layered textile-polymer hybrids to achieve desired flexibility in the material and build.

***Specific Aim #3:***

The purpose of this aim is to train a reinforcement learning (RL) agent that manages brace tension automatically and to evaluate its performance using peak-inversion angle testing. The simulation that was developed will be converted into an RL environment with reward functions based on stability, pressure accuracy, and comfort. The RL agent will learn how to adjust tension in response to changing pressure patterns. Performance will then be assessed using peak inversion-angle analysis through camera footage and applied force to a mock 3D printed ankle. This testing will show the brace's effectiveness in preventing dangerous levels of ankle inversion.

**Justification and Feasibility.** Reinforcement learning provides a framework for continuous mechanical adjustment in situations where pressure changes rapidly. Peak inversion angle is a biomechanically meaningful metric because excessive inversion is associated with ankle sprains.

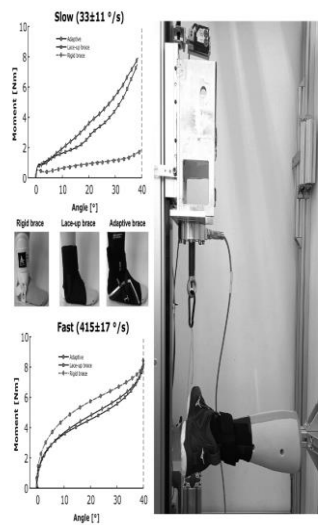


Figure 1. Mechanical tests performed with the artificial ankle (representing the right lower leg and foot) on the different brace conditions. Inversion is induced by pulling the rope connected to the lateral aspect of the foot upwards. All braces were tested with the same shoe as during the biomechanical testing. Results represent the mean of 3 trials per condition.

speeds.

**Expected Outcomes.** The expected outcome of this aim is an RL-based controller that maintains stability more effectively than a nonadaptive brace. Performance improvements are anticipated in both response time and peak inversion angle reduction. These results will demonstrate whether a fully adaptive brace can balance comfort and stabilization without relying on human intervention.

**Potential Pitfalls and Alternative Strategies.** Challenges may include unstable RL policies, difficulty transferring control strategies from simulation to hardware, or hardware limitations. If the RL agent shows unstable behavior, adjustments will be made to the reward structure or the allowed action range. If simulation-to-hardware transfer is difficult, a hybrid model combining ML prediction with constrained RL adjustments may be used. Should hardware limits arise, alternative actuation systems or tension routing strategies will be explored.

### Section III: Resources/Equipment

#### Force Sensitive Resistors

Force-sensing Resistors (FSRs) are a core component of the adaptive system, as they provide the real-

Willawacher et al. (2023) showed that adaptive systems reduce peak inversion angles during fast dynamic movement, making it an appropriate benchmark for evaluating the system's effectiveness. Since the simulation environment is already established, RL training can be performed safely without human participants.

*Figure 3: Willawacher et al. (2023) tested and recorded resistance that rigid, lace up, and adaptive braces had to move. The adaptive brace became more effective at reducing peak ankle angle inversion at faster*

time pressure data needed to determine brace tightening or loosening. These sensors change resistance based on applied force, allowing them to capture subtle variations in ankle load during simulated walking, lateral motion, or inversion. Their thin profile and flexible structure make them suitable for embedding directly into brace material without altering natural movement. Reliable FSR output is essential for developing the pressure-response model and generating labeled datasets for machine learning and reinforcement learning systems.

### **3D Printed Foot Model**

A 3D printed anatomical foot and ankle model will be used as a safe, consistent platform for peak ankle angle inversion testing. The model provides a standardized structure for applying controlled loads and simulating high peak inversion angles without placing human participants in danger of injury. It also enables repeatable tests, precise evaluation of force applied, and the angle being simulated.

### **Arduino Uno**

The Arduino Uno operates as the central control unit for reading sensor data and activating the motor-based tightening system. Its stable 5V logic, accessible GPIO pins, and compatibility with a wide range of sensors make it suitable for rapid prototyping. The Arduino collects high frequency FSR data, executes rule-based control logic, and sends commands to the actuator based on detected pressure changes. The boards' ecosystem of libraries and shields enables quick integration of communication, motor control, and data logging modules, supporting both early sensor calibration, and later validation of ML and RL outcomes.

### **Peak Inversion Angle Motion Capture – Reflective Markers and Fiji ImageJ**

Quantifying peak inversion angle requires motion tracking tools that can measure ankle orientation across frames. Small reflective markers will be attached to key anatomical locations on the brace to

allow frame-by-frame angle calculations. Video footage will be analyzed in Fiji (ImageJ), an open-source scientific imaging platform capable of marker tracking, angular measurements, and data export. This setup makes it possible to perform inversion angle analysis, providing a reliable way to evaluate whether the adaptive brace reduces inversion during simulated instability events.

### Section V: Ethical Considerations

Any data that is included will be stored in secure folders on the cloud with copies saved on a computer hard drive to avoid loss of data.

### Section VI: Timeline

**November.** The goal is to complete preliminary sensor calibration and build graphs for the sensors while additionally sketching out designs for the first and second iterations of the ankle brace

**December.** The goal is to start CADing the second design while simultaneously working on sensor and actuator placement with the real brace. Initial bench testing to validate placement of external hardware.

**January.** The goal is to print the second iteration after making edits using feedback from the first iteration and begin to assemble and test the brace, looking for areas of improvement.

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