Dynamic Mechanical Assessment of Prosthetic Running Blades Using CNT Fabric-Based Strain Sensors

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Abstract – Running blades are sports prostheses used by individuals with lower limb amputation, constructed from fiber-reinforced polymer composites for superior strength-to-weight characteristics. These blades are designed to compress and decompress easily, enhancing athletic performance. However, a significant challenge in their design and use is the difficulty in precisely assessing their mechanical behaviour in vitro. This study explores the use of carbon nanotube (CNT) fabric-based strain sensors to dynamically measure strain on prosthetic blades. A sensor array and signal conditioning circuitry were developed and integrated into a C-shaped blade. The mechanical performance was tested under various conditions, using ANSYS simulations to identify critical stress points. Dynamic data acquisition was achieved through Wi-Fi modules, allowing for detailed analysis of strain distribution during different activities. Sensors were mounted on heel, toe and middle regions of prosthetic blade to test its performance. Various striking trials were performed for different strike locations to imitate different human motions. The results demonstrate that CNT fabric-based sensors provide insights into the strain behaviour of prosthetic blades. Our findings indicate that the strain distribution varies with strike location, with the middle section experiencing the highest strain during flat base strikes while heel and toe strikes exhibit relatively lower strain levels. This strain analysis paves the way for improved design optimisation and customisation of running blades.

Keywords: *Prosthetic Blade, Strain Sensor, CNT Fabric, Data Acquisition, Human Motion*

1. Introduction

Running blades are sport prostheses used by individuals with lower limb amputation. These blades are typically curved and constructed from fiber-reinforced polymer composites[1-2], offering better strength-to-weight characteristics than single-material designs[3-5]. This material allows the blade to compress and decompress easily, helping runners achieve higher speeds than with conventional prostheses. The shape of the blade depends on the user's running task requirements. For jogging or long-distance running, a C-shaped blade is preferred, while sprinters usually use J-shaped blades [6]. These blades are made of multiple layers (30-90 layers) of carbon fiber sheets fused together into a single unit [7].Given the high-impact forces experienced during running, fatigue testing is essential for ensuring the long-term performance, reliability and safety of prosthetic blades. Repeated loading over time can degrade materials, compromising structural integrity and increasing the risk of sudden failure. Key factors such as material composition, layer configuration and blade geometry significantly influence fatigue resistance which makes rigorous mechanical testing essential. Assessing fatigue behaviour under realistic conditions helps identify potential weak points, refine designs and enhance durability, ultimately improving athlete safety and optimising performance.

One of the enduring challenges in the design, prescription and performance evaluation of passive prosthetic devices lies in the limited ability to characterise their mechanical behaviour accurately under controlled in vitro conditions. Such characterisation is essential for understanding stress distribution, assessing durability and evaluating performance under reproducible, standardised loading scenarios. These insights are vital for the iterative refinement of prosthetic blade designs ultimately contributing to improved user comfort, safety and device reliability. Conventional prosthetic development relies heavily on finite element analysis, compliance with ISO certification standards and standardised mechanical testing. While these approaches ensure baseline performance and regulatory compliance, they fall short in capturing the complex individual-specific loading profiles encountered during real-world use. In clinical settings, prosthetists typically prescribe devices based on generalised user parameters such as body weight, height and activity level, rather than leveraging precise dynamic biomechanical data. This limits the scope for fine-tuned personalisation and may compromise optimal prosthetic function for individual users [8].To bridge this gap, dynamic strain monitoring offers a powerful tool for empirically capturing real-time stress distribution across the prosthetic structure during representative gait and activity cycles. Even in systems that do not employ active feedback control such data serves a critical diagnostic and design role. By mapping high-stress zones and characterising localised strain concentrations, designers can proactively reinforce vulnerable regions mitigating the risk of fatigue failure and structural degradation. Furthermore, integrating dynamic patient-specific motion data into the design loop enables the tailoring of devices to the user's biomechanics, thereby enhancing fit, function and responsiveness. The dynamic performance of prosthetic running blades is intrinsically linked to their material composition and mechanical architecture. Key parameters include the elastic modulus which governs stiffness and influences the blade's capacity to flex and recover, crucial for energy storage and return during running. The material density affects the prosthesis's mass and inertial properties impacting ease of movement and comfort. Stress analysis encompassing both tensile and compressive regimes helps in identifying critical stress zones, guiding material placement and structural optimisation. The strain response offers insight into deformation behaviour under load informing design strategies that balance flexibility with mechanical integrity. In addition, the fatigue resistance of the composite material under repetitive cyclic loading is a central determinant of long-term device performance. Repeated impact loading during high-intensity use such as sprinting or jumping can induce microstructural degradation ultimately leading to failure if not properly mitigated. Thus sensor-informed strain analysis not only enhances our understanding of in-use blade mechanics but also supports informed decisions regarding material selection, blade curvature, cross-sectional geometry and layering strategies. These improvements facilitate the design of next-generation prostheses that are structurally robust, biomechanically adaptive and user-personalised.

A promising approach to dynamic monitoring is the integration of carbon nanotube (CNT)-based strain sensors [9-12]. Traditional methods, such as strain gauges[13] and piezoelectric sensors [14], suffer from bulkiness, mass and complex signal conditioning requirements. They also lack the flexibility, durability and sensitivity needed for dynamic applications like running prostheses. In contrast, the CNT fabric-PDMS-based strain sensor developed in this study offers superior flexibility, durability and strain resolution. Its ability to conform to the curved structure of the prosthetic blade ensures accurate measurements without compromising mechanical integrity. A key metric for evaluating the performance of any strain sensor is the gauge factor which quantifies the change in electrical resistance relative to the amount of strain applied. In simple terms, it measures how sensitively a sensor responds to mechanical deformation. A higher gauge factor means that even small strains result in significant changes in resistance enabling the detection of subtle deformations. CNT based strain sensors often show high gauge factors (ranging from ~1 to >1000) depending on the CNT type (single-walled or multi-walled), sensor fabrication and working mechanism [15-16]. The high gauge factor (25.9)[1] of CNT-based sensors allows for improved strain resolution, capturing subtle variations more effectively[16-22]. Beyond prosthetic applications, CNT-based strain sensors have been successfully applied in flexible electronics [21], wearable motion tracking[1], robotics[10] and structural health monitoring [23]. Their mechanical robustness and stretchability under repeated loading make them ideal for high-deformation environments. In the context of prosthetic running blades, the integration of such highly sensitive and flexible sensor arrays enables real-time assessment of mechanical behaviour under dynamic gait conditions aiding in the refinement of blade geometry and material distribution. This supports fatigue mitigation, enhances performance and increases user comfort. The integration of highly sensitive and flexible sensor arrays [24-26] allows real-life assessment of prosthetic mechanical behaviour helping manufacturers in refining blade designs to improve durability and user comfort. Furthermore, wireless data transmission is essential for practical, long-term strain monitoring in prosthetic devices. Unlike wired sensors, which can be cumbersome and restrict movement, wireless sensors enable continuous data collection without interfering with user mobility. This advancement supports iterative improvements in prosthetic design, leading to more adaptive, personalised and resilient solutions.

This study aims to assess how elastic modulus, localised strain, stress transfer and fatigue resistance affect the dynamic mechanical behaviour of prosthetic running blades, which are key to improving responsiveness, durability and user-specific performance. This paper focuses on the development of a CNT fabric-based sensor array and its signal conditioning circuitry to measure strain at multiple locations on a prosthetic blade. It also investigates the integration of the developed wireless sensor array into a C-shaped blade and evaluates the blade mechanical performance during various activities through rigorous testing. This setup will facilitate future product-based research in structural health monitoring [27-31], human motion monitoring [32-33] and strain monitoring of prosthetic running blades [37]. The stress-strain relationships of blades and other curved auxiliary equipment present significant opportunities and urgent needs for exploration.

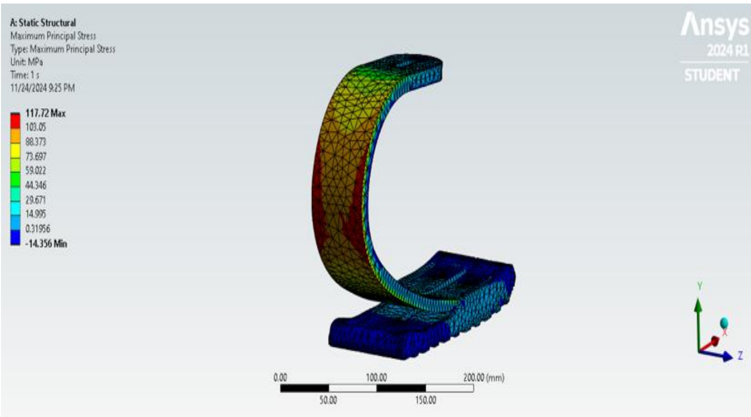
2. ANSYS Simulations

To analyse the performance of prosthetic blades, a 3D model of lower limb prosthetic devices is created using SOLIDWORKS [8] and then imported into the ANSYS toolbox as shown in Fig. 1. For the simulation setup, the blade is fixed at the bottom and a vertical downward force of 1400 N is applied at the top. The data is from a 1.72m tall and 70.9 kg male running at a self-selected speed of approximately 3.1m.s^{-1}.The material used for the blade is

E-glass and epoxy carbon woven 395 Prepeg. The material properties includes density of 1480 kg m^{-3}, orthotropic thermal expansion, elasticity, stress limits and Tsai-Wu constants. The sole is made of polyurethane which has a density of 1265 kg m^{-3} and follows a shock Equation of State (EOS) linear model. This facilitates the analysis process by allowing for a detailed examination of the prosthetic device's behaviour and performance in response to different conditions.

Fatigue testing, a specialised branch of mechanical testing is then implemented. This method involves subjecting the prosthetic device to cyclic loads repetitively and continuously. The primary goal is to identify critical locations within the lower limb prosthetic assembly that may be prone to failure during routine usage. This process helps identify weaker positions in the structure, facilitating improvements to enhance overall strength and increase the device lifespan. Key stress parameters play a significant role in this evaluation. As shown in Fig. 1a, maximum principal stress represents the highest tensile stress experienced under operational conditions. This parameter is critical for preventing cracks or fractures particularly during high-impact activities like running or jumping. Conversely, Fig. 1b illustrates minimum principal stress, which signifies the maximum compressive stress the blade can withstand assessing its ability to resist permanent deformation or structural failure under compressive loads. During running, peak forces on the lower limbs can reach 2–3 times body weight, equivalent to 1400–2100 N for a 70 kg individual, with 1400 N serving as a reasonable baseline for testing. Crack propagation is particularly evident in the curvature of the C-spring blade when a 1400 N load is applied vertically, indicating that potential failure points are concentrated in this region due to maximum stress and deformation in the geometry.

Additionally, Von Mises stress analysis has been incorporated to assess the mechanical performance and potential failure risks of the prosthetic running blade, as illustrated in Fig. 2. The analysis revealed that maximum stress levels occur at the middle inner and outer regions of the blade. Consequently, strain sensors were strategically installed at these critical points to capture stress variations accurately. Additionally, two more strain sensors were positioned at the top outer and bottom outer sections of the blade, as these areas are expected to exhibit significant deformations under compression.



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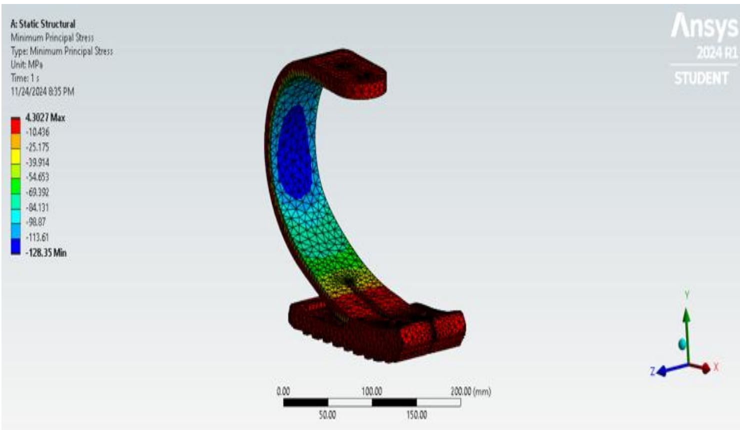


(b)

Figure 1. ANSYS simulation results showing (a) maximum principal stress and (b) minimum principal stress locations in the prosthetic blade

The cyclic loading test results, as shown in Fig. 3, were conducted based on the provided manufacturer data. The blade underwent both experimental testing and simulation for 10,000 cycles with the applied force ranging from 1400 N to 0 N (Fig. 3a). Our analysis revealed that the stress levels after cyclic loading remained below the strength threshold of carbon fiber resin composite [38] (Fig. 3b). Consequently, no visible cracks or delamination were observed, indicating the structural integrity of the blade under the tested conditions.

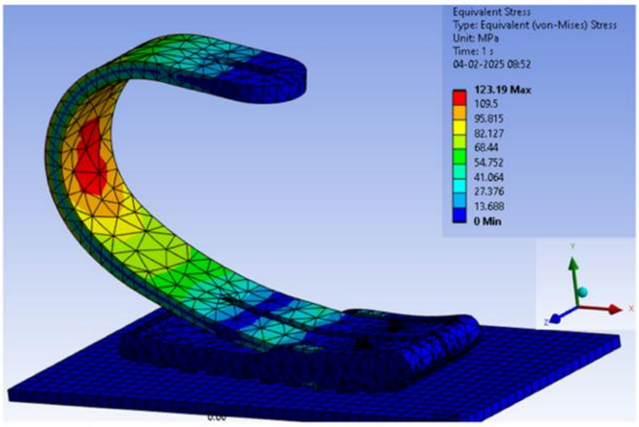
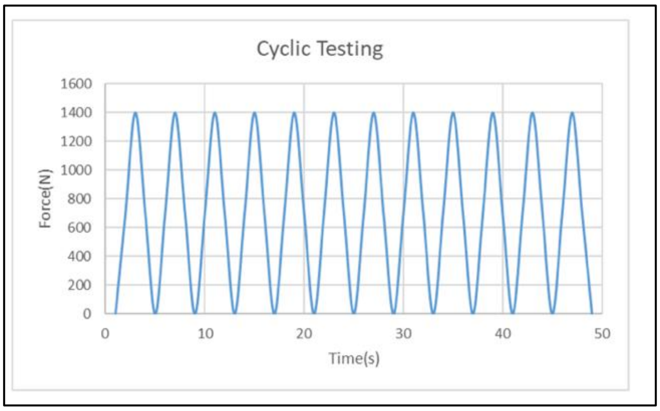
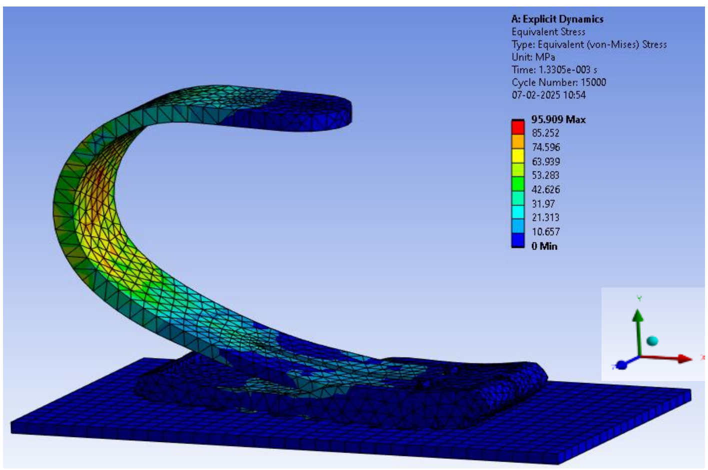


Figure 2. ANSYS simulation results showing Von-Mises stress locations in the prosthetic blade.



(a)



(b)

Figure 3. ANSYS simulation results of the cyclic loading test (a) applied force over time during the loading cycles and (b) simulated response based on manufacturer-provided data.

3. Sensor Array Design and Implementation

3.1. Design of sensor array and circuit components

To examine the mechanical properties of the blade in vitro, a strain sensor array has been designed. As the surface undergoes strain and deforms, the sensor array affixed to it reads the deformation. A data acquisition circuit has been developed to capture these strains. The sensor array used for measuring the necessary strains at different locations on the blade is a flexible array made from polydimethylsiloxane (PDMS) infused with carbon nanotubes (CNT fabric sensor).To fabricate a carbon fabric PDMS nanocomposite film sensor, carbon fabric is first cut to dimensions of 14.98x12.31x0.86mm. Sylgard 184 (PDMS) is then prepared by bath sonication to remove air bubbles and a curing agent is added in a 10:1 ratio. The mixture is stirred gently for 10 minutes using a magnetic stirrer for uniformity. A Teflon mould matching the fabric dimensions is prepared using tape and carbon fabric placed in cavity. The mixture is then poured over the fabric ensuring complete saturation. Afterwards the impregnated fabric is removed from the mould and cured for 80 °C followed by post curing at room temperature for 24 hours. To create robust electrodes, snap buttons were used. Fabric nature of sensors allow insertion of buttons in through the sensor surface as shown in Fig. 4. [1]. This sensor distinguishes itself from other commercially available strain sensors, such as strain gauges and piezoelectric sensors, due to its unique properties. Unlike traditional sensors that primarily measure strain resulting from bending, axial and torsional stresses in a single direction and insensitive to lateral forces. CNT fabric-based sensors are capable of detecting strain from both bending and stretching across multiple directions. This characteristic makes flexible CNT fabric sensors more adaptable for measuring strain on curved surfaces.

The data acquisition unit comprises CNT fabric sensors, transmitter & receiver modules, microcontrollers (MCUs), preamplifiers, analog-to-digital converters (ADC), voltage regulators, and an in-situ data storage module as shown in Fig. 5. This comprehensive setup enables accurate measurement and recording of strains, particularly on the surfaces with varying curvature. The inclusion of a data storage module on the circuit itself, along with dynamic data transmission capabilities, offers flexibility in data processing.

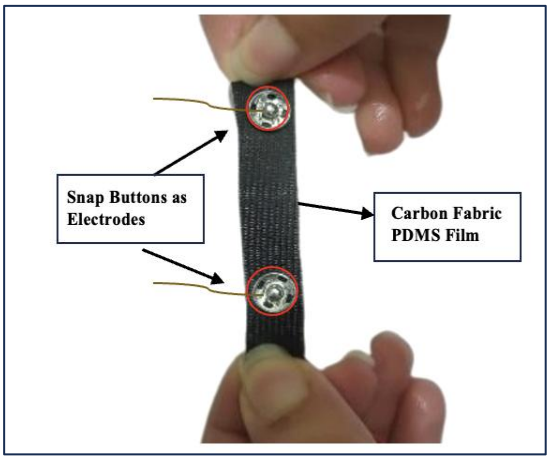


Figure 4. Picture showing the flexible carbon fabric PDMS based strain sensor.

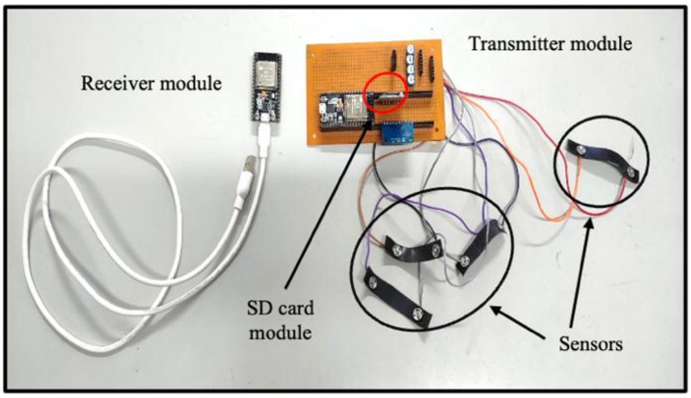


Figure 5. Transmitter and receiver circuits with data acquisition system.

3.2. Dynamic response of sensor array on prosthetic leg

The performance of the sensors and the Data Acquisition (DAQ) system was calibrated and tested by measuring strains on a dummy mechanical prosthetic leg [13] using a process similar to standard human motion monitoring tests. This means that the leg was manually moved to simulate human walking producing voltage signals with frequencies ranging from 1-3 Hz which depends on stride length. For running, the voltage signals generated have frequencies between 3-5Hz depending on the running speed. Sensors were strategically placed on toe, heel and ankle of the prosthetic leg as shown in Fig. 6. The leg was manually moved (see Supplementary Information Fig. S1) to replicate human walking, generating voltage signals with frequencies comparable to human walking and running as shown in Fig. S2 (see Supplementary Information) . These electrical signals were then input into the preamplifier circuit to amplify the voltage signals for further processing. The amplified analog signals were fed into an ADC, which digitised the signals and sent them to electronics programmed to calculate and convert voltage values into corresponding strain values. The final strain data was dynamically displayed on a connected monitor to enable continuous monitoring of sensor response and was simultaneously recorded in an onboard storage module for subsequent analysis. This testing procedure ensured the continuous and accurate assessment of the sensors and data acquisition system performance in capturing and translating strain data from the prosthetic leg.

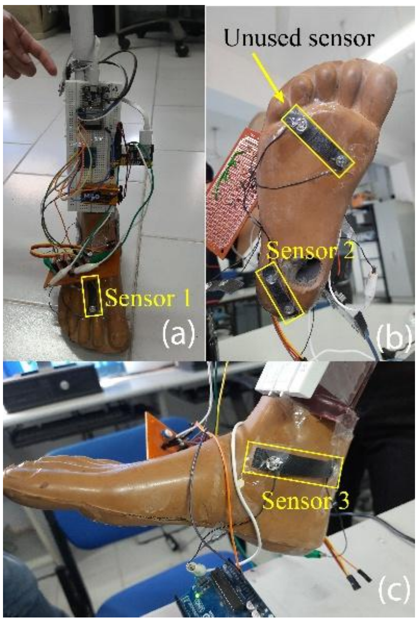


Figure 6. Photos of flexible strain sensor array mounted on the prosthetic leg a) toe, b) heel and c) ankle.

3.3. Integration of sensor on prosthetic blade

Strain tests were performed on a prosthetic blade, with the sensor locations strategically positioned at points identified for higher strain based on ANSYS simulation results as shown in Fig. 7.The compact data acquisition circuit assembled on a perfboard was securely attached to the blade along with the sensors using double-sided nano magic tape ensuring stability without affecting the blade structural integrity. To compensate for sensor bending over the curved surface, the output was calibrated and normalised to nominal values after mounting. As the sensor positions remained unchanged across trials, the calibrated values remained consistent throughout the tests.

A specialised machine was developed with a hydraulically actuated cylinder at the top to simulate varying weight conditions based on a person body mass. Dynamic forces generated by the system were transmitted through a test specimen onto inclined platforms with a single-axis sliding mechanism. This setup accurately replicated biomechanical activities such as walking, running and jumping. The adjustable inclination and controlled sliding motion enabled precise simulation of ground reaction forces under different impact scenarios, allowing for a comprehensive analysis of material behaviour, load distribution and fatigue performance. Integrated sensors and a data acquisition system captured dynamic force, displacement and stress-strain responses, enhancing the evaluation of mechanical performance across diverse activity profiles. This machine enables the evaluation of prosthetic blade performance at different angles of elevation and varying speeds as shown in Fig. 7. A patent for this machine has been published [39].

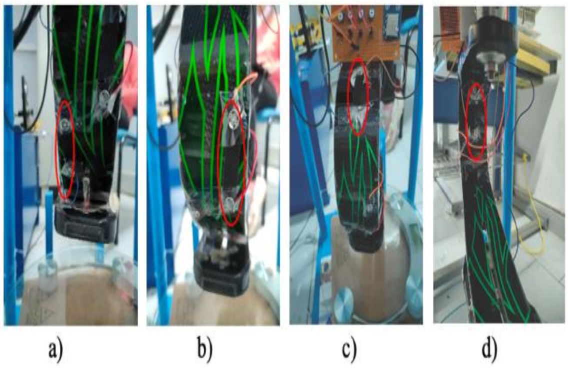


Figure 7. Photos of flexible strain sensors array mounted on the prosthetic blade a) Lower outside, b) Middle outside, c) Top outside and d) Middle inside.

To ensure that the experimental strain tests on the prosthetic blade accurately validated the simulation results, careful attention was given to matching the key assumptions and conditions of the ANSYS simulations with the real-world setup. The ANSYS simulations were used to identify regions of high stress concentration under expected loading scenarios such as walking, running and jumping. These stress hotspots informed the strategic placement of CNT fabric-based strain sensors in the experimental setup. By ensuring that sensors were mounted precisely at the high-strain regions predicted in simulation (as shown in Fig. 7), the experimental results could directly correlate with simulated stress contours allowing for effective validation. In simulation, the blade was subjected to boundary conditions and force vectors representing biomechanical loads. To mimic these in practice, the custom hydraulic testing machine was designed to reproduce dynamic forces corresponding to varying body weights and activity types. The use of an inclined platform with a single-axis sliding mechanism enabled realistic simulation of ground reaction forces and momentum transfer during walking or jumping. These forces replicated the distributed and cyclic loading seen in the simulation model ensuring congruence between simulated and experimental mechanical conditions. Simulations typically include assumptions about the contact surface, motion direction and damping. In the physical setup, this was addressed by tuning the angle of inclination, the speed of the actuator, the material and shape of the platform. This helped replicate both the initial impact and the follow-through movement in a way that matched the simulation scenarios such as heel-strike and toe-off dynamics in gait cycles. The simulations used known mechanical properties of the blade material under expected strain rates. In the experiment, sensor calibration after mounting was crucial for ensuring the output reflected actual strain and not artifacts due to curvature or installation. The sensors were calibrated and normalised post-mounting to offset bending effects and align the measurements with nominal simulated values. In both the simulation and the experiment, time-dependent loading profiles were considered. A real-time data acquisition system with synchronised force, displacement and strain measurements ensured that the transient mechanical responses (especially during impact events) could be directly compared to time-stepped simulation results. By aligning these simulation assumptions i.e. loading profiles, boundary conditions, material properties and measurement locations with the experimental parameters, the study ensured a robust validation framework. This tight integration between simulation design and physical testing increased confidence in both the predictive accuracy of the models and the real-world performance insights gained from the strain measurements. Strains generated during the blade's motion were recorded for further analysis. The impact of elevation angle and the first point of contact on strain distribution was studied.

4. RESULTS AND DISCUSSIONS

4.1 Transmission and reception of data

Data transmission and reception were made possible through Wi-Fi modules integrated into microcontrollers. The ESP32 development boards were chosen for their multitasking capabilities, low power consumption and robust performance. These boards are equipped with an onboard Wi-Fi module, antenna and power pins, simplifying data pre-processing and peripheral module management. Both transmitter and receiver microcontrollers are programmed accordingly. The sampling rate used in this system is 100 Hz for walking as shown in Fig. 8. This sampling rate is same for tests done in both outdoor and indoor conditions. While studies in the literature often use 200 Hz [14] for running gait analysis, our system prioritises efficient data transmission while maintaining sufficient resolution for practical applications. The output signal from preamp circuit is fed to transmitter microcontroller unit (MCU). This high-resolution data is pre-processed at transmitter side and then written on peripheral data storage module and simultaneously transmitted to a corresponding module that serves as the receiver at 9600 baud rate. The signal received by receiver module can then be visualised by monitor connected to read the data as shown in Fig. 8. The achieved range for transmission was approximately 150 meters without loss of data as shown in Fig. 9. Both the receiver and transmitter ends are fully capable of displaying and storing the strain data on their respective ends.

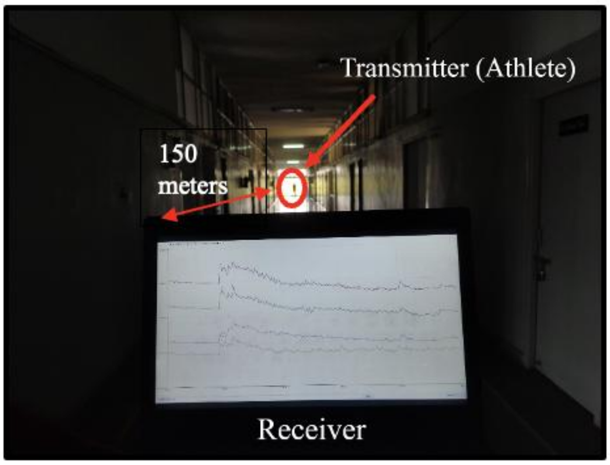
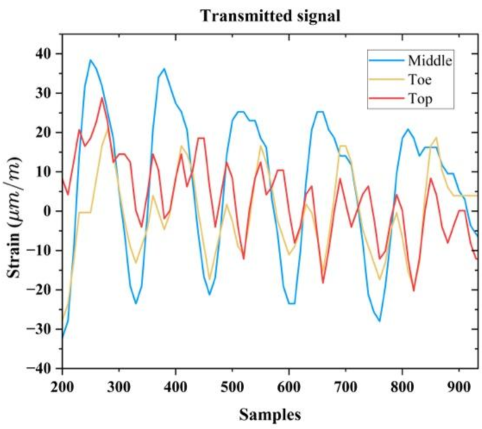


Figure 8. Photo showing the distance between signal transmission and receiving ends.



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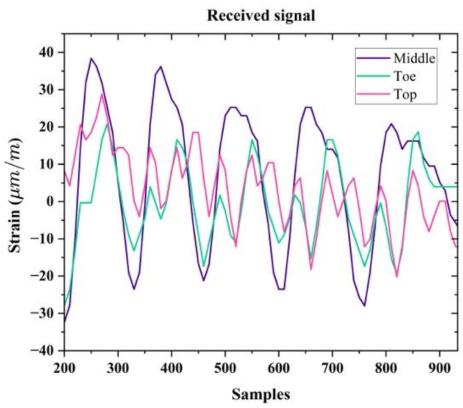

b)

Figure 9. Signals of three flexible strain sensors array mounted on the prosthetic blade at a) transmitter side and b) receiver side.

4.2 Response and settling time of developed sensor

Sensors exhibit a transient response during the initial phase of stretching and relaxation. After this period, the sensor response stabilises to some extent but still shows some reduction in resistance. The transient response accounts for artifacts caused by strain sensing circuitry. This low signal amplitude should not be mistaken for overshooting, as it is not related to the sensor's material properties. The gradual decrease in resistance over time has also been reported in previous studies involving carbon nanotube (CNT)-based sensors [6][9]. This trend represents a well-known transient behaviour characteristic of CNT-based sensing materials [40–41].For our CNT fabric sensors, the percentage decline in resistance over 100 cycles of stretching and relaxation is approximately 2%.

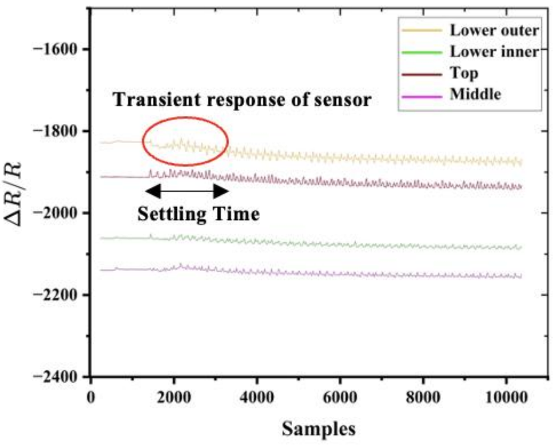

Figure 10. Transient response of all four sensors.

4.3 Sensor integration and strain transfer analysis in prosthetic blade

In line with prior studies on biomechanical load assessment during human gait [1], strain measurements were conducted on a prosthetic running blade to evaluate its structural response under dynamic loading. These tests considered variations in gait cycle frequency representing both slow and fast walking conditions. A comprehensive set of experiments was performed using an in-house developed machine [39], enabling controlled testing of the blade's mechanical response under different contact conditions namely flat-footed strikes, toe strikes and heel strikes. Each of these conditions was further analysed at varying blade-ground contact angles to emulate realistic landing scenarios. Numerical simulations revealed initial strain localisation in the toe region with strain progressively transferring towards the mid-blade and heel as the loading cycle advanced. These simulation results aligned well with empirical strain data obtained from the sensor network integrated along the C-shaped geometry of the blade. Three primary trial configurations were evaluated, categorised based on the point and angle of first contact: flat base, toe strike and heel strike. In the flat base condition, strain measurements were recorded over a sequence of seven gait cycles. As depicted in Fig. 11, sensor responses vary depending on their spatial placement with the corresponding sensor locations as illustrated in Fig. 7. The inner and outer middle sections of the blade exhibited the highest strain amplitudes consistent with the simulation results and are represented by the green and blue curves in Fig. 11. Notably, the strain propagated in a temporally sequential manner: initiating at the toe region (~10 μm/m), intensifying in the mid-blade (~30 μm/m) and tapering at the top (~8 μm/m), as indicated by the red, green/blue and yellow traces respectively.

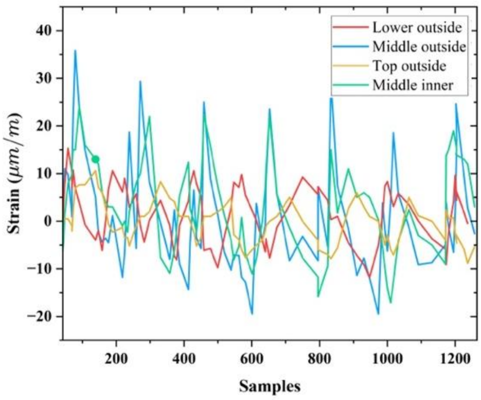

Figure 11. Strain sensors response for flat base strike at lower, top and middle sections of blade

Figure 12 illustrates the sensor response for a toe strike scenario executed at a 15° blade-ground contact angle. As anticipated, the sensor positioned near the toe region registered a significantly elevated strain response compared to the flat base trial. This is attributed to the concentrated impulse loading during the initial contact phase, reinforcing prior findings on localised stress peaks during forefoot loading.

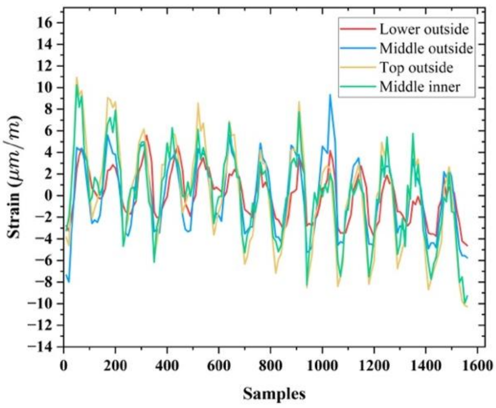

Figure 12. Strain sensors response for toe strike lower, top and middle sections of blade.

In the heel strike trials (Fig. 13), sensor placement was limited due to the lack of structural support near the heel region where only the shoe pad makes contact. Consequently, strain data was not recorded directly from the heel. Nonetheless, the strain patterns from the remaining sensors indicate reduced activity in the toe region and peak responses centered around the mid-blade affirming the shift in load transfer associated with heel-first contact dynamics. All sensor responses during heel strikes remained within the expected operational strain window further validating the sensor array's robustness and the predictive accuracy of simulation models. Overall, the correlation between experimental and simulated strain distributions substantiates the effectiveness of the CNT-fabric-based sensor network in capturing spatially and temporally resolved mechanical behaviour across varied locomotion profiles. This integrated approach not only supports more nuanced insights into load path evolution in prosthetic designs but also contributes to ongoing efforts in personalised optimisation of prosthetic performance through sensor-informed feedback systems.

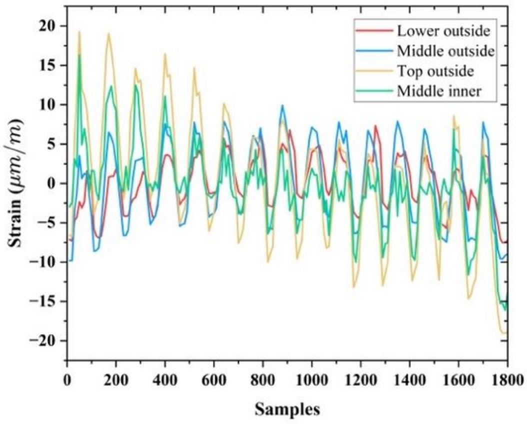

Figure 13. Strain sensors response for heel strike lower, top and middle sections of blade.

5. CONCLUSIONS

This study presents a significant advancement in the dynamic evaluation and optimisation of prosthetic running blades through the integration of a flexible, wireless strain-sensing system based on CNT fabric embedded in a PDMS matrix. By embedding these sensor arrays along the curved C-shaped geometry of the blade, the system enables high-resolution real-time monitoring of mechanical behaviour during varied gait conditions. Traditional strain gauges and piezoelectric sensors while useful in static or quasi-static scenarios often underperform under dynamic and multi-axial loading due to limitations in flexibility, sensitivity and integration complexity. In contrast, the CNT fabric-based sensors demonstrated in this study offer superior mechanical compliance, a high gauge factor (25.9) and the ability to conform to complex surfaces without interfering with the blade function enabling accurate and multi-directional strain detection. The wireless data acquisition system featuring onboard storage and Wi-Fi modules with a transmission range of approximately 150 meters enhances the practicality and usability of the sensing platform for extended laboratory use and potential on-field deployment. Dynamic trials involving flat base, toe strike and heel strike conditions were conducted to evaluate strain distribution at four distinct blade locations. The results consistently revealed that the middle section of the blade experienced the highest strain magnitudes especially during flat base impacts (~30 µm/m) followed by lower peak values at the heel and toe regions (~10 µm/m). The inner mid-section also exhibited strain but with a slightly lower magnitude (~8 µm/m). These experimental findings aligned closely with ANSYS simulations which predicted initial stress concentrations at the toe propagating through the mid-blade to the heel. This simulation-experiment agreement validates the reliability of the integrated system and underscores its potential to guide targeted reinforcement and geometric optimisation of prosthetic components for improved fatigue resistance and impact mitigation. In conclusion, the integration of CNT fabric-based strain sensors into prosthetic running blades represents a promising step toward the development of more adaptive, personalised and high-performance prosthetic solutions for individuals with lower limb amputations. The ability to dynamically monitor mechanical responses under realistic loading opens new possibilities for performance tuning, failure prevention and user-specific design. Future research should focus on refining sensor fabrication techniques, improving calibration protocols, and expanding this sensing framework to other high-performance prosthetic and orthotic devices used in sports and physical rehabilitation.

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Credit authorship contribution statement

Lisa Verma: Experimental investigation, Methodology, Writing – original draft**.** **Isha Karnawal:** Experimental investigation, Methodology. **Shivam Jadaun:** CAD modelling and Simulations**,** Testing Support**. Puneet Kumar:** CAD modelling and Simulations**. Praveen Kumar:** Sensor Fabrication, Formal Analysis, Validation **Daman Preet Singh:** Medical Guidance, Visualisation, Supervision **Cleveland Barnett:** Conceptualization, Resources, Supervision, Funding acquisition, Project administration. **Shukri Afasov** Data Analysis, Supervision, Validation. **Paul Felton** Data Analysis , Supervision, Validation. **Philip Breedon** Supervision, Resources, Project administration. **Rajesh Kumar** Conceptualization, Resources, Supervision, Project administration. **Gaurav Sapra** Conceptualization, Resources, Writing-review & editing, Supervision, Funding acquisition, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that support the findings of this study are available upon reasonable request from the authors.

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