Design and Development of an Instrumented Insole for Gait Profiling

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Summary

Monitoring plantar pressure and gait is crucial for mobility preservation and diagnosing foot pathologies, particularly diabetic foot conditions. This study presents the development of a wireless insole-footwear system to measure plantar pressure distribution using ten force-sensitive resistors (A301, A401, A502) strategically placed at key foot locations. Data acquisition is managed via a multiplexer and an ESP32 microcontroller with a Wi-Fi-enabled configuration. A signal conditioning circuit enhances sensor sensitivity. The device efficiently captures data at a 100 Hz sampling frequency, making it well-suited for walking analysis. Real-time data is accessible via a web application, stored, and analyzed in MATLAB (R2023b). A Butterworth filter with a cutoff frequency of 2–4 Hz is applied for noise reduction. The filtered pressure data is analyzed to compute ground reaction forces (GRF) and detect gait events such as heel strike, toe-off, and mid-stance, providing valuable insights for gait assessment and abnormality detection.

Introduction

Accurate plantar pressure and gait measurements play a crucial role in diagnosing foot disorders, preventing injuries, and improving rehabilitation outcomes. Advances in sensor-embedded insoles enable precise monitoring of plantar pressure and gait parameters [1,2]. While previous studies have explored various sensor configurations, there is limited research on optimizing the minimum number of sensors required to develop an effective, low-cost, indigenous insole for plantar pressure and gait analysis.

Methods

The insole consists of three layers—top, middle, and bottom—where the sensors are embedded within the middle layer, designed with thermoplastic polyurethane (TPU) material for enhanced comfort and support. The system integrates an ESP32 microcontroller and ten force-sensitive resistors positioned across key anatomical regions of the foot. Data is wirelessly transmitted via Wi-Fi to a graphical user interface for visualization, recording, and storage. To validate the system, trials were conducted with ten healthy volunteers walking a 3 m distance after providing informed consent. The collected data were analyzed to extract key plantar pressure and gait parameters.

Results and Discussion

The typical gait cycle (Figure 1) of an 80 kg volunteer revealed higher force values under the heel during the stance phase. This is due to initial ground contact and weight-bearing of the volunteer imposed on the sensors. During terminal stance, a peak force was observed highlighting the propulsion phase. Peak force values were highest at heel strike (893±37 N) and were found to decrease slightly during toe-off (878±32N), with mid-stance showing lower force application (636±39 N). Force distribution patterns indicated that forefoot and heel regions experienced the highest loads, varying based on volunteer weight and walking style. Variability analysis showed a standard deviation of ±15 N in repeated trials, confirming measurement consistency. Additionally, gait cycle duration was found to range between 0.98 and 1.12 s across volunteers, demonstrating minor inter-individual variability. Each gait cycle was segmented from the full trial, and key gait events such as heel strike, mid-stance, and toe-off were detected (Figure 2(a)).

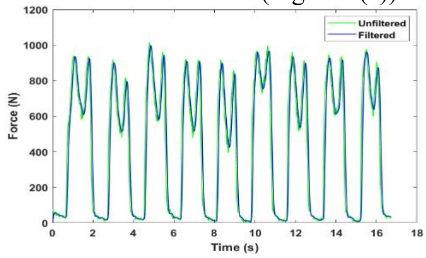

Figure 1: Typical ground reaction force of one trial (Left foot).

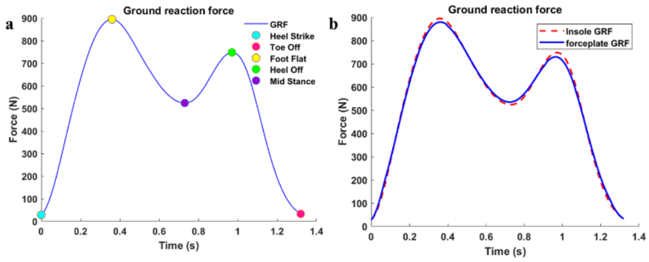

Figure 2: Typical ground reaction force of one gait cycle.

A comparison of GRF data between the force plate and the insole device (Figure 2(b)) showed a root mean square error (RMSE) of 12.23±0.28 N. Additionally, correlation analysis produced an R^2 value of 0.99, indicating a strong correlation. The mean gait parameters such as the total walking time (16.50±0.58 s), the estimated walking speed (0.18±0.02 m/s), the average step time (1.85±0.13 s), the estimated cadence (32.30±2.13 steps/min), average stance time (1.36±0.07 s) and estimated step length (0.35±0.02 m) for all the volunteers were obtained. These findings confirm the system's accuracy in monitoring plantar pressure and GRF values, showing a strong correlation with measurements from Kistler's force plate. The developed insole offers valuable insights for diagnosing foot conditions, gait correction, and rehabilitation interventions.

Conclusions

An indigenous insole with embedded sensors was developed to measure plantar pressure for gait analysis and gait detection. It provides real-time pressure distribution and gait parameters. The system is adaptable for personalized footwear and applications like foot reflexology.

References

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