Design and Development of an Automated Electromechanical Knee Ankle Foot Orthosis: An Innovative Sensor Based Programmable Device

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Abstract: The condition of knee-deficient patients is commonly characterized by quadriceps weakness and knee instability during gait, leading to compensatory walking patterns and reduced functional mobility. Conventional locked knee ankle foot orthoses (KAFOs) provide stance-phase stability but restrict knee flexion during swing and increase metabolic cost. This study aimed to design and develop an Automated Electromechanical Knee Ankle Foot Orthosis (AEMKafo) that ensures stance-phase stability while permitting free knee motion during swing. A custom-molded polypropylene KAFO was integrated with a force sensing resistor, Arduino UNO microcontroller, lithium-ion battery, and a solenoid-based magnetic locking mechanism. Heel contact detection triggered automatic knee locking during stance, while pressure release initiated unlocking to allow swing-phase flexion. The fabricated prototype demonstrated reliable sensing, timely actuation, smooth gait-phase transitions, and stable mechanical engagement during bench testing. These findings confirm the technical feasibility of a sensor-driven stance-control KAFO and support further optimization and clinical validation for knee-deficient patients.

Keywords: *Knee Ankle Foot Orthosis, Femoral Neuropathy, Quadriceps Weakness, Stance Control Orthosis, Automated Electromechanical Devices, Gait Analysis, Rehabilitation.*

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I. INTRODUCTION

Femoral neuropathy and knee deficient persons represents a significant clinical challenge affecting lower limb motor and sensory function, with prevalence estimated at 2-8% of the adult population [1]. The femoral nerve, the largest branch of the lumbar plexus originating from spinal levels L2-L4, provides innervation to the quadriceps femoris, hip flexor muscles, and sensory perception to the anterior thigh and medial leg [2]. Etiology of femoral neuropathy encompasses multiple mechanisms including direct trauma, prolonged compression from surgical positioning, hip arthroplasty complications, diabetic neuropathy, retroperitoneal hemorrhage, and pelvic fractures [1]. Regardless of etiology, femoral nerve dysfunction results in characteristic clinical presentations: quadriceps weakness or paralysis, loss of knee extension capability, sensory loss in the anterior thigh and medial leg, and inability to extend the knee against gravity, manifesting as knee buckling during weight-bearing activities [2,3]. These functional deficits critically impact ambulation, with patients demonstrating characteristic gait deviations including crutch gait and hand to knee gait, which substantially increase metabolic cost and energy expenditure during ambulation [4]. Traditional orthotic management utilizes knee ankle foot orthoses with locked knee mechanisms such as drop ring locks and bail locks, providing rigid support throughout the gait cycle. While locked KAFOs prevent knee buckling during stance phase, they necessitate compensatory gait mechanisms including circumduction, vaulting, hip hiking, and lateral trunk lean to accomplish swing phase advancement of the limb [5,6]. These compensation patterns increase metabolic demand, reduce walking velocity, limit functional speed capacity, and compromise gait symmetry [6,7].

Recent advances in orthotic design have introduced stance control mechanisms that mechanically and electronically permit free knee flexion during swing phase

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while maintaining rigidity during stance phase [8]. These systems substantially reduce gait deviations and metabolic cost compared to conventional locked KAFOs [7,9,10]. However, many existing designs suffer from complexity, excessive weight, bulky profiles, limited cosmetic acceptance, high cost, and delayed activation response [5,10,11]

This project proposes development of (AEMKafo) incorporating miniaturized components—force sensing resistor, microcontroller processing unit, compact lithium-ion battery, and magnetic solenoid locking mechanism—integrated with custom-molded thermoplastic orthosis shell to provide responsive stance phase stability with unrestricted swing phase flexion. The design prioritizes component minimization, reduced overall weight, improved cosmetic appearance, economic feasibility, and reliable activation response.

II. REVIEW OF LITERATURE

- Stance-Control Orthoses (SCOs) allow knee locking during stance and automatic unlocking during swing, thereby improving gait efficiency and reducing compensatory movements [6,7]. Studies report improved cadence, walking speed, and reduced energy consumption compared with conventional locked KAFOs [6–9]. However, many SCO systems remain mechanically complex, bulky, and expensive, limiting widespread clinical adoption.

- Electromechanical and Sensor-Based KAFO Systems employing motors, solenoids, or clutches have demonstrated reliable knee locking-unlocking synchronized with gait phases [8–11]. Sensor-based approaches, particularly using force sensing resistors (FSRs), offer a simple and robust method for detecting ground contact and triggering actuation [12]. These systems show promise in improving response time and reducing device complexity compared with purely mechanical SCO designs.

- Need for Simplified and Cost-Effective Designs have technological advances, many current electromechanical KAFOs suffer from high cost, increased weight, and limited cosmetic acceptance [10,11,13]. There is a clear need for compact, lightweight, and economically feasible stance-control KAFOs that integrate simple sensor-based detection with reliable electromagnetic actuation to enhance functional mobility in individuals with femoral neuropathy [6,9,14].

III. MATERIALS AND METHODS

- *Study Design:*

This investigation comprised biomechanical device development and functional evaluation of an automated electromechanical KAFO prototype designed for patients with femoral neuropathy.

- *Design Concept:*

The AEMKafo operates on stance control principles, distinguishing between stance and swing phases through pressure-activated sensing. The fundamental design philosophy centers on providing automatic knee joint locking exclusively during stance phase to prevent buckling while enabling free knee flexion during swing phase to facilitate natural limb advancement without compensatory mechanisms.

- *Design Components*

- *Mechanical Components*

✓ *Custom-Molded Orthosis Shell:*

Thermoplastic polypropylene (6 mm) fabricated through traditional casting and molding procedures to obtain anatomically contoured thigh shell and ankle-foot orthosis components. Medial and lateral uprights (aluminum) connect the thigh shell to the ankle-foot section, with modification eliminating the traditional drop lock mechanism on the medial side.

✓ *Mechanical Locking Mechanism:*

Solenoid-driven lever system positioned on the lateral upright at the knee joint level. The lever incorporates a mechanical extension piece that moves vertically (downward to lock, upward to unlock), controlling knee joint rigidity through engagement/disengagement with the orthotic knee structure.

- *Electrical Components*

✓ *Force Sensing Resistor (FSR SEN8 39.1 mm):*

Conductive polymer pressure sensor mounted beneath the heel of the ankle-foot orthosis. The FSR demonstrates variable resistance proportional to applied pressure, detecting ground contact at heel strike (activation) and loss of contact at toe-off (deactivation).

✓ *Microcontroller Unit (Arduino UNO ATMEGA328P):*

8-bit microcontroller processing pressure signals from the FSR and generating appropriate output commands to the solenoid locking unit. Programming logic implements threshold detection (pressure above/below activation threshold) and signal filtering to prevent chatter artifact.

✓ *Power Supply (12V Li-ion Battery):*

Rechargeable lithium-ion battery (capacity appropriate for continuous daily use) positioned within a protective sheath lateral to the thigh shell, minimizing pressure on sensitive tissues while maintaining discreet profile.

✓ *Magnetic Solenoid Locking Unit (12V DC):*

Electromagnet-operated solenoid providing controlled mechanical switching of the lever position. Energization produces electromagnetic force drawing the lever downward (knee locked); de-energization permits lever upward movement (knee unlocked) via mechanical spring return.

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- *Electrical Circuit Architecture*

The circuit integrates the FSR sensor, microcontroller, solenoid, and power supply in a series–parallel configuration. The FSR is connected to an analog input with a pull-down resistor, while the solenoid is controlled through a digital output pin. A common ground is maintained for all components, and the battery supplies regulated power to the system, ensuring stable sensing, reliable switching, and efficient power management (Fig.1).

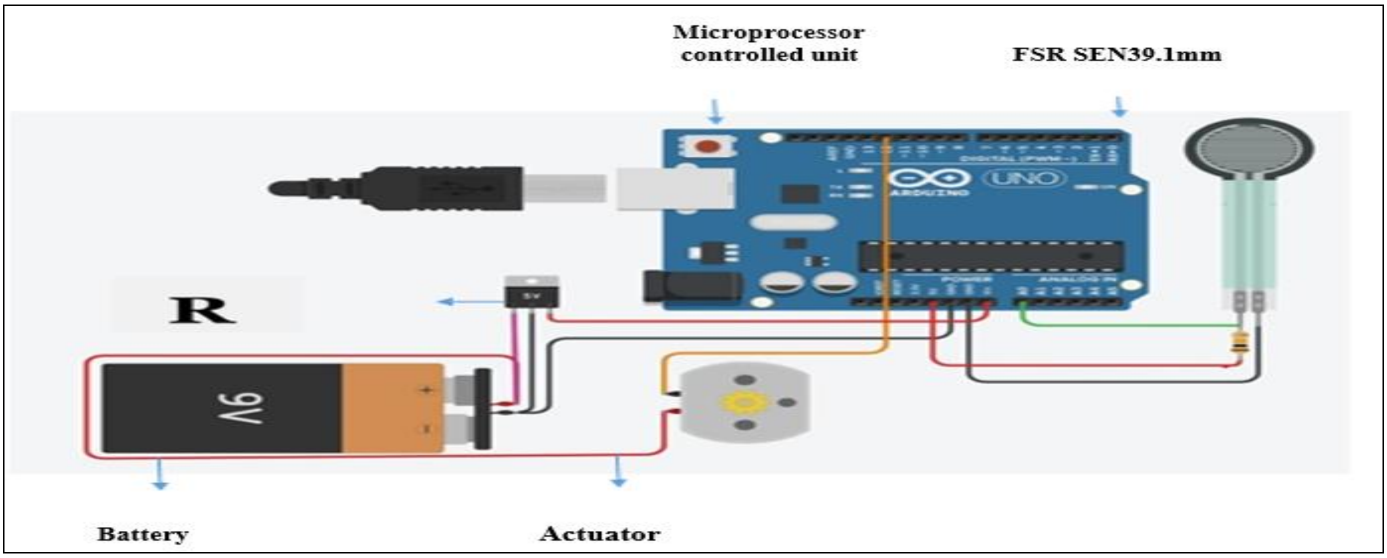

Fig 1 Circuit Diagram

Patient casting was performed in the supine position with the pelvis stabilized in neutral alignment. A protective stockinet was applied from the toes to the proximal thigh, followed by circumferential wrapping with plaster of Paris bandages. Key anatomical landmarks were identified and marked, with the knee maintained in full extension and the ankle positioned at 90°. After setting, reference lines were drawn and the negative cast was separated into thigh and ankle–foot sections**.** (Fig. 2)


Fig 2 Fabrication Procedure of a Knee-Ankle –Foot- Orthosis (KAFO)

Positive Molds were produced using plaster slurry and subsequently modified to achieve appropriate contouring, trimlines, malleolar relief, smooth shank contours, and total-contact arch support. Six-millimetre polypropylene sheets were heated to 180 °C and vacuum-formed over the Molds, trimmed, and finished to final boundaries allowing adequate clearance for knee motion. Aluminium uprights were fabricated to predetermined measurements and riveted without conventional manual locks. The solenoid locking unit was mounted on the lateral upright, while the microcontroller and 12 V battery were housed in a protective lateral thigh pocket. The FSR sensor was positioned beneath the heel within a resilient pad, and all electrical connections were secured with proper insulation and strain relief. Finally, 3-mm ethaflex padding was applied to all contact surfaces, completing the Automated Electromechanical Knee Ankle Foot Orthosis (AEMKafo)(Fig.3).

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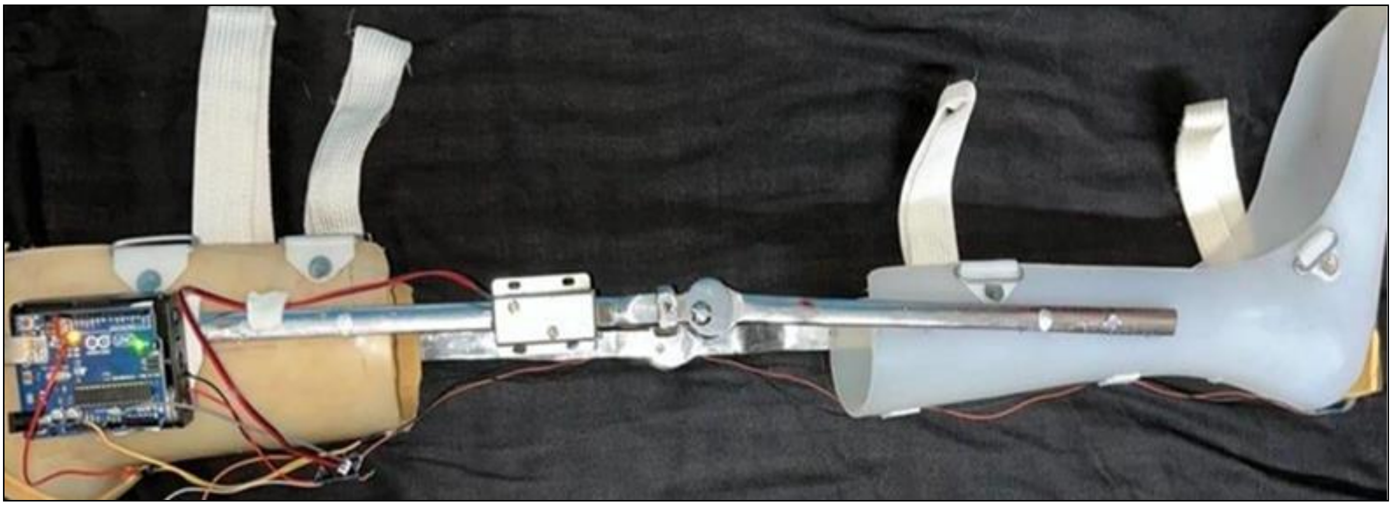

Fig 3 Final Assembly

➤ *Functional Testing*

- *Sensor and Actuation Verification:*

Manual loading and unloading of the heel region were performed to validate FSR signal detection and corresponding ON/OFF states. Solenoid actuation was assessed by confirming electromagnetic engagement of the locking lever upon sensor activation and disengagement following pressure release.

- *Operational Cycle Testing:*

Repeated stance–swing simulation cycles were conducted to evaluate consistency of the locking–unlocking sequence, system responsiveness, and absence of mechanical interference or actuation delay.

- *Structural and Alignment Assessment:*

Static standing trials were used to verify proper orthotic alignment, component positioning, and maintenance of knee extension at simulated ground contact.

Motion and system performance observations demonstrated that sensor activation during the simulated foot-flat condition consistently initiated knee locking, while pressure reduction in late stance triggered timely unlocking. The unlocking mechanism permitted unobstructed knee flexion during swing without mechanical resistance. Additionally, kinematic observations of knee flexion during swing and knee extension during stance will confirmed the intended mechanical behaviour of the system in future work.

IV. RESULT

The Automated Electromechanical Knee Ankle Foot Orthosis (AEMKafo) was successfully fabricated with complete integration of mechanical and electronic subsystems, without structural or electrical complications. The prototype demonstrated appropriate anatomical conformity, comfortable interface characteristics, and a low-profile cosmetic design suitable for clothing concealment. Functional testing confirmed reliable FSR pressure detection with consistent activation–deactivation and absence of chatter. The solenoid locking unit exhibited rapid and repeatable actuation in response to microcontroller commands, with no mechanical binding or delayed response across more than 100 operational cycles. Activation times occurred within the millisecond range, enabling smooth and synchronized transitions between stance-locking and swing-unlocking modes. Static alignment assessment verified stable upright posture, secure knee extension during load-bearing, and symmetrical weight distribution. During simulated gait conditions, heel loading consistently initiated knee locking, while pressure reduction triggered timely unlocking, allowing free passive knee flexion and restoration of extension prior to terminal swing. Qualitative system-level observation indicated smooth mechanical behavior with reduced reliance on compensatory motion patterns. The total device weight was approximately 3.5–4.0 kg, with all components discreet positioned and demonstrating consistent functional reliability throughout testing.

V. DISCUSSION

This study successfully demonstrates the design, fabrication, and evaluation of an automated electromechanical KAFO prototype that overcomes key mechanical limitations of conventional locked knee orthoses through sensor-driven stance-control functionality. The device illustrates a practical implementation of stance-control orthosis principles using simplified architecture and miniaturized electronic components integrated within a conventional KAFO framework. The principal technical achievement is the development of an automatic pressure-responsive knee locking–unlocking mechanism that provides phase-specific control of joint rigidity, enabling rigid support during load-bearing conditions and free motion during non-load-bearing conditions. This design approach represents a substantive advancement over constant-locking systems and establishes a scalable platform for further engineering optimization and system refinement.

➤ *Mechanistic Advantages Over Traditional KAFOs*

Conventional drop-lock and bail-lock knee mechanisms rely on manual operation or constant locking, which inherently limits dynamic adaptability. The AEKFO introduces a sensor-driven, pressure-responsive control strategy that enables automatic transition between locked and unlocked states in synchrony with load-bearing conditions.

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The use of an FSR-based sensing approach offers a direct and robust method of detecting weight-bearing through force thresholds that naturally correspond to ground reaction forces, eliminating the need for complex gait-phase algorithms. The solenoid-based locking mechanism provides consistent electromagnetic engagement, offering a compact and reliable alternative to friction-dependent clutch systems or bulky motor-driven actuators.

- *System-Level Design Benefits:*

The AEMKafo architecture emphasizes component miniaturization, reduced mechanical complexity, and simplified electronics. A compact solenoid replaces larger motors and multi-linkage actuation systems commonly used in earlier electrically actuated KAFOs, thereby reducing overall volume and weight while preserving functional reliability. The selection of commercially available components, including a microcontroller platform, standard FSR, and DC solenoid, supports cost-effective fabrication and scalability. Discrete component placement and a low-profile configuration improve cosmetic acceptability without compromising structural integrity.

In addition, the event-driven power strategy—where the solenoid is energized only during load-bearing conditions—optimizes energy consumption and supports efficient power management. Collectively, these design features establish a robust, economical, and scalable stance-control KAFO platform suitable for further engineering refinement and system optimization.

➢ *Potential Limitations and Future Considerations*

This initial development work primarily established the technical feasibility and functional integrity of the automated electromechanical KAFO. System evaluation was based on qualitative observations of sensor response, actuator behaviour, and mechanical transitions. Future development should incorporate quantitative kinematic and kinetic characterization using motion capture, force platforms, and EMG to define system performance more precisely. Formal measurement of electrical-to-mechanical latency is also required to characterize response timing relative to gait cycle events. Long-term reliability testing is necessary to assess component durability, battery performance, and maintenance requirements under extended use.

The current design employs a simplified FSR-based gait-phase detection strategy focused on fundamental stance-phase stabilization. Future iterations may integrate inertial sensors to improve phase-detection robustness and adaptability to variable walking conditions. Unlike complex adaptive stance-control systems, the AEMKafo is intentionally positioned as a pressure-responsive, cost-effective platform with reduced component complexity. This design philosophy supports scalability, ease of fabrication, and suitability for resource-limited settings. Collectively, these features provide a strong foundation for continued engineering refinement and system optimization.

Fig 4 Final Design of AEMKafo

VI. CONCLUSION

The automated electromechanical KAFO integrates pressure-responsive sensing with electromagnetic actuation to enable dynamic stance-phase support and unrestricted swing-phase knee flexion. The design overcomes key limitations of conventional locked KAFOs through automatic phase-responsive control, compact architecture, and cost-effective component selection. Functional develop confirmed reliable sensing, rapid solenoid response, and smooth transitions between locking and unlocking states, supporting the technical feasibility of the system.

FUTURE WORK

Future work will focus on quantitative gait analysis using instrumented motion capture and force platforms, multi-user validation, long-term durability and battery performance testing, and refinement of phase-detection through additional sensor integration. Further optimization of lightweight materials, compact control hardware, and power management strategies is expected to enhance efficiency, portability, and overall system performance.

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