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RESEARCH ARTICLE

Biomechanical Evaluation of a Modified Floor Reaction Orthosis with Pneumatic Knee Joint in Quadriplegic Cerebral Palsy: A Single-Patient Pilot Case Study

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ABSTRACT

Background: Crouch gait, characterized by excessive knee flexion during stance, is a common and debilitating gait abnormality in children with cerebral palsy (CP). Conventional floor reaction orthoses (FROs) utilize ground reaction force (GRF) manipulation to promote knee extension; however, rigid designs offer limited dynamic control in children with significant hamstring tightness and proximal spasticity.

Objective: To evaluate the biomechanical and metabolic effects of a modified floor reaction orthosis incorporating a pneumatic knee joint (mFRO-PKJ) in a single child with spastic quadriplegic cerebral palsy.

Methods: A single 7-year-old female child with spastic quadriplegic CP (GMFCS Level II) underwent gait assessment while walking a 5-m walkway with and without the mFRO-PKJ. Spatiotemporal gait parameters and metabolic cost were assessed using clinical gait measures and a portable metabolic system (Cosmed K4b2).

Results: In this single patient, use of the mFRO-PKJ resulted in improvements in step length, stride length, cadence, and walking velocity, along with a reduction in oxygen consumption during ambulation. Qualitative observations indicated improved trunk alignment and reduced compensatory movements.

Conclusion: In this single-patient pilot case study, the mFRO-PKJ demonstrated promising biomechanical and metabolic benefits in managing crouch gait. These findings suggest that pneumatic-assisted FROs may offer a biomechanically informed alternative to conventional rigid designs; however, further controlled studies with larger samples are necessary to establish generalizability.

Keywords: Cerebral palsy, Floor reaction orthosis, Pneumatic knee joint, Crouch gait, Gait biomechanics, Energy expenditure, Single-case study

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INTRODUCTION

Cerebral palsy (CP) is a non-progressive neurodevelopmental disorder with a global prevalence of approximately 1.5–3 per 1,000 live births and is characterized by motor impairments including spasticity, muscle weakness, and impaired selective motor control.[1] Among the various gait abnormalities observed in CP, crouch gait, defined by excessive hip and knee flexion and increased ankle dorsiflexion during stance, is particularly disabling due to its association with increased energy expenditure and progressive functional decline. [2-6]

Orthotic management plays a central role in non-operative treatment strategies for crouch gait. Floor reaction orthoses (FROs) are designed to manipulate the ground reaction force (GRF) by limiting ankle dorsiflexion and positioning the GRF vector anterior to the knee joint, thereby generating an external knee extension moment during stance.[4] While effective in selected patients, conventional rigid FRO designs often fail to adequately control knee flexion in children with marked hamstring tightness and proximal spasticity.[5-8]

To address these limitations, this study introduces a modified floor reaction orthosis with an integrated pneumatic knee joint (mFRO-PKJ). The design aims to combine GRF-

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Figure 1: Modified Floor Reaction Orthosis with Pneumatic Knee Joint (mFRO-PKJ) - Front, Lateral, and Posterior views showing anterior tibial shell, posterior calf and thigh shells, pneumatic cylinder, and pressure adjustment mechanism.

based ankle control with adjustable, dynamic resistance at the knee joint, providing graded extension assistance and continuous passive stretching of the hamstrings during gait. This paper presents a single-patient pilot case study evaluating the biomechanical and metabolic effects of this novel orthotic intervention.

LITERATURE REVIEW

Crouch gait results from a complex interplay of plantarflexor weakness, hamstring contracture, and abnormal neuromuscular control.[3-9] Biomechanical studies have demonstrated that even modest improvements in knee extension during stance can significantly reduce metabolic cost and improve walking efficiency in children with CP.[10]

Traditional FROs and floor reaction ankle-foot orthoses (FRAFOs) have shown improvements in knee kinematics and extensor moments in children with mild contractures and adequate hip control.[7-12] However, their inability to dynamically modulate knee flexion moments limits effectiveness in more severe presentations.[5-13]

Recent advances in orthotic technology have explored dynamic and adaptive components, including spring-based and pneumatic systems, to better replicate physiological joint behavior.[14,15] Pneumatic mechanisms offer adjustable resistance and damping characteristics and have demonstrated feasibility in assistive and orthotic devices, including pediatric applications.[16,17]

Assessment of energy expenditure provides an objective measure of functional impact. Portable metabolic systems such as the Cosmed K4b2 have been validated for field-based gait analysis and are sensitive to changes in gait efficiency following orthotic intervention.[18–20]

Materials and Methods

Study Design

A single-subject pilot case study was conducted at the National Institute for Locomotor Disabilities (Divyangjan), Kolkata. The study design involved within-subject comparison of gait parameters and metabolic cost with and without the mFRO-PKJ.

Participant

A 7-year-old female child with spastic quadriplegic CP (GMFCS Level II) participated in this study. The participant presented with crouch gait, hamstring spasticity (Modified Ashworth Scale 2+), and limited knee extension during stance. No orthopedic surgery had been performed within the previous 18 months. The participant was able to ambulate independently with assistive devices and demonstrated cognitive ability to follow simple instructions during gait assessment.

Table 1: Comparative gait and metabolic parameters (Mean ± SD of 3 trials)

Parameter	*Without orthosis (Mean ± SD)*	*With mFROPKJ (Mean ± SD)*	*Absolute change*	*Percentage change*
Step length (m)	0.16 ± 0.01	0.17 ± 0.01	+0.01	+6.25%
Stride length (m)	0.32 ± 0.02	0.34 ± 0.02	+0.02	+6.25%
Cadence (steps/min)	17 ± 2	32 ± 3	+15	+88.2%
Velocity (m/s)	0.46 ± 0.03	0.91 ± 0.04	+0.45	+97.8%
VO_2 (ml·kg^{-1}·min^{-1})	12.5 ± 0.8	10.8 ± 0.7	-1.7	-13.6%

SD: Standard Deviation

Figure 2: Posterior and Lateral View of child standing with modified FRO

Orthosis Design and Fabrication

Design Overview

The mFRO-PKJ consisted of a custom-molded polypropylene anterior tibial shell with posterior calf and thigh shells. The ankle was fixed in 5–7° plantarflexion to facilitate anterior GRF positioning. A compact pneumatic cylinder providing adjustable damping and extension assistance was mounted posterior to the knee axis. Pneumatic resistance could be tuned by altering cylinder pressure (expressed in Newtons) to modulate knee extension assistance.

Fabrication Workflow

The fabrication process followed a systematic sequence

- *Assessment*

Clinical evaluation of the participant included range of motion assessment, muscle tone evaluation using the Modified Ashworth Scale, and observational gait analysis to determine orthotic requirements.

- *Casting*

Negative casts of the participant›s lower limb were obtained using plaster of Paris bandages with the ankle positioned in 5–7° plantarflexion and the knee in approximately 10 to 15° flexion to accommodate the crouch posture.

- *Modification and Rectification*

Positive plaster models were modified to accommodate pressure-tolerant and pressure-sensitive areas, ensuring optimal fit and force distribution. Biomechanical modifications were made to align the ground reaction force vector anterior to the knee joint axis.

- *Moulding*

The orthosis was fabricated using 5 mm thick polypropylene sheets, which were heated in a convection oven at 160 to 180°C and vacuum-formed over the rectified positive model. The anterior tibial shell, posterior calf shell, and posterior thigh shell were fabricated as separate components.

- *Assembly of Pneumatic Knee Joint*

A compact pneumatic cylinder (6N) was mounted posterior to the knee joint axis using aluminum brackets. The pneumatic system was connected via flexible tubing to a pressure adjustment valve and a small portable air reservoir. The knee joint mechanism incorporated a hinge joint aligned with the anatomical knee axis.

- *Alignment*

The assembled orthosis was aligned on the participant to ensure proper sagittal and coronal plane alignment. The knee joint axis was positioned to coincide with the anatomical knee joint center. The ankle-foot section was aligned 5 to 7 degree plater flexion to achieve appropriate GRF vector positioning.

- *Pressure Adjustment*

Initial cylinder pressure was set to 12 N and subsequently adjusted based on the participant’s comfort and gait response. Pressure adjustments were made in increments of 6 N, with final pressure determined by clinical observation of knee extension during stance.

- *Gait Training*

The participant underwent a 2-hour familiarization training period with the orthosis, including walking practice, standing balance activities, and instruction on proper use.

Testing Protocol

Participant Familiarization

Prior to formal data collection, the participant underwent a

2-hour familiarization gait training session with the mFRO-PKJ. This session included instruction on donning and doffing the device, practice walking along the test walkway, and time to accommodate the pneumatic resistance.

Gait Assessment Procedure

The participant walked along a 5-m walkway at a self-selected comfortable pace under two conditions: (1) barefoot walking without orthosis (baseline), and (2) walking with the mFRO-PKJ. Testing was conducted in the same indoor environment with consistent floor surface and lighting conditions.

Walking Trials

Three steady-state walking trials were recorded for each condition. A trial was considered steady-state when the participant demonstrated a consistent gait pattern without start-up or termination effects. The middle 3 m of the 5-m walkway was used for data collection to minimize acceleration and deceleration effects.

Metabolic Data Collection

Metabolic data were collected using the Cosmed K4b2 portable metabolic system. The system was calibrated according to the manufacturer's instructions before each testing session

Calibration Procedure

- Room air calibration was performed to establish baseline gas concentrations

Figure 3: Child standing without orthosis

- Gas calibration was conducted using a certified reference gas (16% O_2, 4% CO_2) to calibrate the oxygen and carbon dioxide sensors
- Flow meter calibration was performed using a 3-L syringe according to manufacturer specifications
- Turbine calibration was verified to ensure accurate volume measurement
- The participant wore the Cosmed K4b2 system during each walking trial. Oxygen consumption (VO_2) was recorded continuously throughout each trial.

Outcome Measures

- Primary Outcomes
- Step length (m)
- Stride length (m)
- Cadence (steps/min)
- Walking velocity (m/s)
- Oxygen consumption (VO_2, $ml \cdot kg^{-1} \cdot min^{-1}$)
- Secondary Outcomes
- Trunk posture (qualitative observation)
- Hip hiking (qualitative observation)
- Compensatory movements (qualitative observation)
- Subjective comfort and perceived effort (participant report)

Data Analysis

Mean and standard deviation (SD) were calculated for each parameter across the three steady-state trials for both conditions. Absolute change and percentage change were calculated to quantify the effect of the intervention. Data were analyzed descriptively given the single-subject design.

RESULTS

The mFRO-PKJ resulted in improvements across all measured parameters (Table 1).

The large improvements observed in cadence (88.2% increase) and walking velocity (97.8% increase) likely reflect multiple contributing factors: improved knee extension mechanics reducing the energy cost of stance, reduced crouch posture decreasing the muscular demand for postural support, enhanced confidence and stability allowing for more rapid ambulation, and the inherent variability associated with single-case measurements. The magnitude of these changes, while substantial, should be interpreted cautiously given the single-subject design.

Qualitative assessment revealed improved trunk alignment, reduced hip hiking, and smoother rocker progression during stance. The child reported reduced effort and good tolerance to the device. No adverse events or skin irritation were observed during the testing period.

DISCUSSION

This single-patient pilot case study evaluated the biomechanical and metabolic effects of a customized Modified Floor Reaction Orthosis with a Pneumatic Knee Joint (mFRO-PKJ) in a child with spastic quadriplegic cerebral palsy presenting with crouch gait. Compared with walking without the orthosis, the participant demonstrated improvements in step length, stride length, cadence, walking velocity, and oxygen consumption, indicating enhanced gait efficiency and functional mobility.

Unlike conventional rigid floor reaction orthoses (FROs), which rely primarily on ankle positioning to generate an external knee extension moment, the proposed mFRO-PKJ incorporates an adjustable pneumatic knee mechanism that provides dynamic resistance during stance while allowing controlled knee flexion during swing. This design may offer improved knee stability, facilitate gradual hamstring stretching, and reduce compensatory trunk and hip movements during walking.

The marked improvements observed in cadence and walking velocity are likely attributable to improved knee extension during stance, enhanced postural stability, and increased walking confidence with the orthosis. Similarly, the reduction in oxygen consumption suggests improved walking efficiency, which is consistent with previous reports demonstrating that improved lower-limb alignment can reduce the metabolic cost of gait in children with cerebral palsy.

Although the present findings are encouraging, they represent the outcome of a single participant and should therefore be interpreted cautiously. Further studies involving larger cohorts, longer follow-up periods, and comprehensive biomechanical analyses are required to determine the clinical effectiveness and broader applicability of the proposed orthotic design.

Interpretation of Findings

The substantial increase in walking velocity and reduction in oxygen cost align with prior evidence linking improved knee extension mechanics to reduced metabolic demand.[10,20] The 97.8% increase in walking velocity, while notable, may reflect both improved gait mechanics and increased confidence with the orthosis.

The 13.6% reduction in oxygen consumption is clinically meaningful in the context of pediatric CP, where even modest improvements in gait efficiency can significantly impact functional mobility and participation. This reduction likely results from decreased muscular effort required for knee extension during stance and reduced reliance on compensatory strategies.

Clinical Significance

For children with quadriplegic CP and crouch gait, orthotic interventions that provide dynamic knee control may offer advantages over traditional rigid designs. The mFRO-PKJ's ability to address both the passive (hamstring tightness) and active (spasticity) components of crouch suggests potential utility in this challenging patient population.

The customized fabrication process allows for patient-specific optimization of alignment, pressure settings, and fit, potentially improving comfort and compliance compared to off-the-shelf devices.

LIMITATIONS

This study has several limitations. First, it represents a single-patient pilot case study, limiting the generalizability of the findings. Second, the absence of a control group or comparison with a conventional floor reaction orthosis prevents definitive conclusions regarding the specific contribution of the pneumatic knee mechanism. Third, only short-term outcomes were evaluated; therefore, the long-term effects on gait, functional mobility, and musculoskeletal development remain unknown. Finally, gait assessment was limited to clinical spatiotemporal parameters and metabolic measurements, without three-dimensional gait analysis, kinetic assessment, or electromyography, which could have provided a more comprehensive biomechanical evaluation. Future studies with larger sample sizes and long-term follow-up are required to validate these preliminary findings.

Future Directions

Future studies should include

- Larger cohorts with heterogeneous presentations of CP
- Randomized controlled trials comparing mFRO-PKJ to conventional FROs
- Instrumented 3D gait analysis for comprehensive kinematic and kinetic assessment
- Longitudinal follow-up to evaluate long-term effects on gait, function, and musculoskeletal health
- Evaluation of optimal pressure settings and their relationship to clinical outcomes
- Assessment of user satisfaction, compliance, and quality of life outcomes

CONCLUSION

In this single-patient pilot case study, the Modified Floor Reaction Orthosis with a Pneumatic Knee Joint demonstrated promising improvements in gait biomechanics and energy efficiency in a child with quadriplegic cerebral palsy. The findings suggest that pneumatic-assisted FROs represent a novel orthotic strategy for managing crouch gait; however, further controlled studies with larger samples and comprehensive outcome measures are necessary before broader clinical recommendations can be made.

ETHICAL CONSIDERATIONS

This manuscript reports a single-patient Pilot study conducted as part of routine clinical assessment and orthotic management at the treating institution. The work was undertaken as a clinical service evaluation to assess the biomechanical and functional performance of a customized modified floor reaction orthosis with a pneumatic knee joint (mFRO-PKJ). No experimental intervention beyond standard clinical orthotic practice was performed. The participant and her legal guardian received a detailed explanation regarding the purpose of the clinical evaluation, orthotic fabrication, gait assessment procedures, expected benefits, and potential risks before participation. Written informed consent was obtained from the participant's legal guardian for the use of anonymized clinical information, photographs, gait analysis data, and publication of this case report. Participation was voluntary, and the guardian was informed that consent could be withdrawn at any stage without affecting the participant's clinical care.

CONFLICT OF INTEREST

The authors declare no conflict of interest. No commercial entity provided funding or support for this study.

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