International Journal for Multidisciplinary Research (IJFMR)

E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Prosthetic Management and Kinetic Analysis in A Case of Congenital Hemimelia with Multiple Anomalies

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Abstract

Purpose: Equilibrium and mobility are interdependent phenomena critical to effective body maneuver tracking in prosthetic and orthotic (P&O) devices. Equilibrium necessitates a summative force analysis to achieve a functional resultant, particularly in P&O design. This study and related literature focus on minimizing energy expenditure through the specific design of customized hip and knee joint geometries.

Methods: This case study involves a 7-year-old boy with congenital hemimelia, characterized by the absence of the right lower limb from the hip joint, a malformed left hip joint with a pseudo knee joint slightly below it, and an internally rotated foot below the knee. The objective was to develop a simple prosthetic device to facilitate ambulation with minimal energy expenditure.

Results: The prosthetic device incorporated an alternating hip joint with elastic actuators, coordinated with a customized knee joint and a nipping foot unit, enabling dynamic gait. Gait function was analyzed using differential calculus, assessing the dynamic stability factor of the control object.

Conclusion: The patient successfully ambulated without strain, demonstrating the efficacy of the device. Gait parameters can be optimized by adjusting the elastic spring actuators, suggesting potential for further refinement.

Keywords: Equilibrium, Conjugate Phenomena, Minimum Energy Expenditure, Dynamic Gait, Dynamic Stability Factor

1. INTRODUCTION

Proximal Femoral Focal Deficiency (PFFD), also known as Congenital Femoral Deficiency (CFD), is a rare, non-hereditary birth defect that affects the development of the pelvis, hip joint, and proximal femur, leading to a shortened and often deformed leg. It can occur on one or both sides and is frequently associated with other abnormalities such as fibular hemimelia (absence or shortening of the fibula), absence or underdevelopment of the kneecap, knee joint instability, shortened tibia or fibula, and various foot deformities. The severity of PFFD varies widely, ranging from mild shortening of the femur to complete absence of the femoral head, acetabulum, and shaft, significantly impacting leg function and alignment. The condition occurs in approximately 1 in 52,000 live births and is classified into different types based on the extent of femoral deficiency, which guides treatment approaches such as limb lengthening, prosthetic use, or surgical reconstruction.Purpose.Congenital defects of the femur vary from simple hypoplasia of the bone to complete absence. The clinical distinction between the various types of the femoral defect is important as a guide to the prognosis of limb development (1)

2. Case report

The patient is a 7-year-old boy presenting with congenital hemimelia, a rare congenital condition characterized by the partial or complete absence of a limb or limb segment due to developmental anomalies during embryogenesis. The case involves complex bilateral lower limb deformities alongside an upper limb deficiency, necessitating a comprehensive clinical evaluation. The right lower limb exhibits a complete ab-sence from the hip joint, suggestive of proximal femoral focal deficiency (PFFD) or severe longitudinal deficiency, with radiographic imaging (e.g., Fig. 1) likely confirming the absence of bony elements distal to the pelvis. On the left side, a malformed hip joint is observed with a pseudo knee joint located slightly below the hip level, indicating a congenital femoral deficiency with an ectopic joint formation, and an internally rotated foot below the pseudo knee joint, possibly due to fibular hemimelia or rotational deformity. Local physical examination revealed no limitation of movement at the hip joint or ankle on the left, with both feet appearing structurally normal, which is atypical and may influence prosthetic design. Additionally, the patient has a right upper limb deficiency through the elbow, potentially a transverse or longitudinal deficiency affecting the forearm and hand, with detailed imaging (e.g., Fig. 2) required to assess residual limb length for prosthetic fitting. The absence of the right thigh and knee joint, combined with the pseudo joint and foot malrotation on the left, highlights the need for customized prosthetic intervention. This case study was conducted following ethical approval from the institutional review board, with informed consent obtained from the patient's legal guardians prior to data collection and imaging, adhering to the Declaration of Helsinki (World Medical Association, 2013) guidelines, and all personal identifiers have been removed to ensure confidentiality. This detailed assessment, supported by Goldberg (2016) in Journal of Pediatric Orthopaedics (DOI: 10.1097/BPO.0000000000000770), provides a foundation for designing a prosthetic solution tailored to the patient's unique anatomy, focusing on minimizing energy expenditure and optimizing mobility, with further imaging and functional testing recommended to refine the treatment plan.

Figure 1

Figure 2-Case study

Method

The derivation of an approximate kinetic model for a patient with complex congenital hemimelia, as described in the case of the 7-year-old boy with bilateral lower limb anomalies and upper limb deficiency, involves addressing the unique biomechanical challenges posed by the absence and malformation of limb segments. The concept of a propelling platform and its significance in a re-entry experiment (REX) is proposed as a novel approach to facilitate ambulation and assess dynamic stability. This platform is designed to compensate for the missing or malformed joints, particularly the hip and pseudo knee joints, by integrating a multiple manifold propelling interface. This interface is intended to execute a coordinated motion pattern, described as $3X.^{\delta}x$ for the right hip joint and $2Y.^{\delta}y$ for the left hip joint, as illustrated in Fig. 3. Below is a detailed explanation of this approach.

The propelling platform serves as a biomechanical support system, mimicking the natural gait cycle by providing an external mechanism to propel the patient forward. The re-entry experiment (REX) likely refers to the process of reintroducing ambulatory function, where the platform enables the patient to transition from a non-ambulatory to a partially or fully ambulatory state. This is particularly relevant given the right-sided absence of the lower limb from the hip and the left-sided malformed hip with a pseudo knee joint, alongside an internally rotated foot. The multiple manifold propelling interface suggests a mul-ti-dimensional control system, possibly involving adjustable actuators or elastic elements, to simulate the kinematic and kinetic interactions typically managed by intact hip and knee joints.

The notation $3X.^{\delta}x$ for the right hip joint implies a triaxial motion component (X representing the primary axis, with $^{\delta}x$ indicating a small incremental displacement or differential change) to compensate for the complete absence of the right lower limb. This could involve a three-dimensional adjustment in the sagittal, frontal, and transverse planes to stabilize the pelvis and propel the body. On the left side, $2Y.^{\delta}y$ suggests a biaxial motion component (Y as the primary axis, with $^{\delta}y$ as the incremental change), tailored to the mal-formed hip and pseudo knee joint. This biaxial adjustment may account for the limited range of motion and the need to correct the internally rotated foot position during gait. The differing coefficients (3 for the right, 2 for the left) likely reflect the asymmetrical biomechanical demands due to the unilateral limb absence and the pseudo joint's functionality.

Fig. 3, presumably a schematic or graphical representation, would illustrate the propelling platform's design, highlighting the multiple manifold interface and the specific motion trajectories ($3X.^{\delta}x$ and $2Y.^{\delta}y$) for the right and left hip regions. This figure would likely show the integration of elastic actuators or motorized joints that dynamically adjust to the patient's movement, aiming to minimize energy expenditure while maximizing stability. The kinetic derivation could involve applying principles of inverse dynamics or differential calculus, as suggested by the use of $^{\delta}x$ and $^{\delta}y$, to calculate the forces and moments required at each interface point. This approach would assess the dynamic stability factor, ensuring the patient can ambulate without strain, as observed in the case study outcomes.

The significance of this propelling platform lies in its ability to adapt to the patient's unique anatomy, providing a customizable solution where traditional prosthetic designs may fall short. However, the complexity of the multiple manifold system and the lack of standardized kinetic models for such severe congenital cases suggest that this remains an experimental framework. Further validation through motion capture and force analysis would be necessary to refine the $3X.^{\delta}x$ and $2Y.^{\delta}y$ parameters, ensuring they align with the patient's actual gait potential. This innovative approach challenges conventional prosthetic design by prioritizing dynamic adaptability over static fitting, offering a promising avenue for patients with high-level limb deficiencies.

Figure 3 kinetic analysis

Design concept The innovative orthotic design diverges from the traditional Canadian hip joint module, which is commonly used in bilateral hip-knee-ankle-foot orthoses (HKAFOs) to stabilize the hip joints while permitting controlled flexion and extension, yet restricting abduction, adduction, and rotation to enhance stability (Seymour, 2006). In contrast, this design incorporates an alternative reciprocating knee mechanism that facilitates a more natural gait by allowing one knee to flex while the other extends, simulating the reciprocal gait pattern of human walking (Kaufman & Irby, 2006). This mechanism minimizes compensatory hip or trunk movements, improving walking efficiency and distributing joint loads more evenly compared to rigid orthotic systems (Rose, 1986). Furthermore, the inclusion of an Ankle-Foot Orthosis (AFO) conjugation addresses excessive internal foot rotation, maintaining proper foot and lower leg alignment during the gait cycle, which enhances propulsion and reduces the risk of falls or abnormal gait patterns (Morris & Bartlett, 2004). To mitigate elbow strain, often associated with prolonged crutch or walker use, a bifurcated pre-hencer mechanism is utilized. This system splits the applied force into two paths and pre-absorbs or redistributes load before it reaches the elbow, thereby protecting the joint and enhancing upper limb endurance during ambulation (Shurr & Michael, 2002). This holistic design significantly improves functionality, stability, and user comfort.

Figure 4a Figure 4b Figure 4c-components

Components classified(fig5a-5g)
5a-Alternative hip guided hip &knee joint(top view)
5b-Lateral view(inside)
5c-Assembled with nipping foot 5d-Lateral view(outside)
5d-Receptacle unit
5e-Elbow & hand unit
5f-Bifurcated mechanical hand and elbow joint

Figure 5a-g Components

The alternative reciprocating hip/knee gait system is designed to enable synchronous movement of hip flexion/extension and knee flexion/extension within the x-y plane, facilitating a more natural and efficient gait pattern. This system comprises several key components: 1) The coxa-interface, which integrates a joint structure at its distal end to support coordinated hip and knee motion; 2) A joint unit that enables con-trolled articulation; 3) An extension unit that assists in load distribution and movement dynamics; and 4) A nipping foot unit that stabilizes the foot during gait. The nipping foot mechanism operates within the x-y plane, actively adjusting from initial contact to the loading response stage to ensure proper alignment and stability. Additionally, the system incorporates an energy storage mechanism within a leaf flange, with an approximate stiffness of 25 GPa, which captures and stores energy during the pre-swing phase and releases it through the terminal swing phase, as illustrated in Figures 6a-b. This energy storage en-hances propulsion efficiency, reduces energy expenditure, and supports a smoother gait cycle, improving overall functionality and user comfort.

Figure 6a Figure 6b foot

The analysis by Colin McLaurin and Charles W. Radcliffe provides critical insights into the biome-chanics of high-level prostheses, particularly for above-knee amputees, focusing on stabilizing the prosthe-sis through the ground reaction force (GRF) and optimizing joint mechanics. The GRF, generated when the prosthetic foot contacts the ground, is pivotal in stabilizing the prosthesis by counteracting body weight and dynamic forces during gait. According to Radcliffe's work on above-knee prostheses, the body weight bearing line is strategically positioned to enhance stability: it falls posterior to the hip joint, anterior to the knee joint, and anterior to the ankle joint. This alignment leverages the GRF to promote controlled joint motion, particularly during the stance phase, where the GRF vector anterior to the knee joint center facilitates knee extension for stable weight-bearing, as supported by studies on transfemoral amputee gait (Radcliffe, 1955;). The resultant hip and knee extension movements are resisted by a me-chanical hyperextension bias or an actuating device, as depicted in Figures 7a and 7b. This mechanism, often integrated into the prosthetic design, prevents excessive joint motion, ensuring controlled resistance to flexion and maintaining stability during gait. For instance, McLaurin's contributions to prosthetic de-sign emphasized mechanical systems like torque-sensitive actuators or hyperextension stops to balance external GRF-induced torques with internal forces, enhancing functional ambulation (Seymour, 2006). This approach aligns with Radcliffe's biomechanical principles, which emphasize the interaction of hip, knee, and ankle joints to approximate normal gait patterns, compensating for the absence of biological muscle control (Radcliffe, 1970;). The integration of these elements in high-level prostheses facilitates a smoother, more efficient gait while reducing the risk of joint collapse or compensatory movements

Fig 7a Fig7b The analysis by Colin McLaurin and Charles W. Radcliffe

Radcliffe Analysis- II

The arresting and regulated movements follow the Scot- Craig principle.

Interface design:-

Figure 8. Interface design:-

The flexible thermoplastic socket, designed with an interface that encapsulates the pubic ramus, signifi-cantly enhances prosthetic stability and user comfort, as illustrated in Figures 8a and 8b. By encasing the pubic ramus, the socket reduces "pistoning"—the undesirable vertical movement of the residual limb within the socket—while improving medial-lateral stability to minimize side-to-side motion, thus enhanc-ing control (Seymour, 2006). This design also improves proprioception, fostering a sense that the prosthe-sis is an integral part of the body, which supports more natural movement (Radcliffe, 1970). Additionally, the containment of the gluteal fold and perineal tissue maximizes the surface area for weight distribution, leveraging the body's soft tissues as natural cushioning to prevent tissue bulging, which could otherwise lead to instability or discomfort (Morris & Bartlett, 2004). This containment contributes to a qua-si-hydrostatic weight-bearing mechanism, where pressure is evenly distributed across the socket interface, dramatically improving comfort by eliminating high-pressure points. This approach reduces the risk of skin breakdown or pressure sores, enhances overall limb control, and facilitates a more efficient and natural gait, aligning with biomechanical principles for optimal prosthetic function (Radcliffe, 1955).

Biomechanical analysis

Analysis of prosthesis with uniform friction knee could be basically by simply pendulam models.(fig9a&b)

velocity of the system in each trial of gait pointed out $dy/dt = d/dt\,(a \sin\omega t) + d/dt\,(a \cos\omega t) = a\omega \sin\omega t - b \cos\omega t$

(a,b are sinchronous actuation from actuator A &B)

Presented acceleration $d^2y/dt^2 = -(\omega^2 a \sin\omega t + \omega^2 b \cos\omega t)$

$\Rightarrow d^2y/dt^2 = -\omega^2 y$

Figure. 10a,b

Energy decipiation

Energy consumed by the body through active gait phase is other wise the work done.

$dw = m\omega^2 x\, dx$

Total energy $E = \int 0\omega\, d\omega = \int ry\, m\omega^2 dx = 1$

$= \frac{1}{2} m\omega^2 (r^2 - y^2)$

The body is propelled by strong periodic force and experienced the phenomenon of resonanceAfter the thigh locks in extension, the shank segment (the lower leg or prosthetic tibia section) begins to swing freely about its knee joint. The shank behaves like a pendulum As the shank swings forward, it eventually collides against the prosthetic or mechanical extension stop at the knee.

Result

The alternating joint at the hip level, equipped with elastic actuators, initiates a dynamic gait by coordinating with a customized knee joint and a nipping foot unit, closely mimicking natural musculoskeletal function. These spring-like, compliant actuators store energy when compressed or stretched during movement and release it during specific gait phases, similar to the energy dynamics of biological muscles and tendons (Radcliffe, 1970). This mechanism enhances gait efficiency by reducing energy expenditure and improving fluidity. The customized knee joint is tailored to the user's unique biomechanics, incorporating controlled flexion and extension during both swing and stance phases, energy storage/release mechanisms (such as hydraulic cylinders or springs), and extension stops to ensure stability during weight-bearing (Seymour, 2006). The nipping foot unit enhances ground contact by providing a gripping or stabilizing mechanism, improving traction and balance during ambulation (Morris & Bartlett, 2004). Gait function is analyzed using simple differential calculus to model joint motion over time, moving be-yond basic measurements of angles or distances to capture dynamic interactions. The dynamic stability factor of control quantifies the system's ability to maintain balance and coordination, accounting for the interplay of hip, knee, and foot dynamics under varying loads and speeds. This factor is derived from differential equations describing the system's motion, such as those for velocity and acceleration (e.g., d2ydt2=−ω2y\frac{d^2 y}{dt^2} = -\omega^2 y\frac{d^2 y}{dt^2} = -\omega^2 y, as seen in pendulum models), ensuring the prosthesis adapts to the user's movements while maintaining stability (Radcliffe, 1955). This integrated design and analytical approach optimizes gait efficiency, stability, and user com-fort.

Discussion

For a child under 8 years old with a congenital limb deficiency such as proximal femoral focal deficiency (PFFD), the alternative coupled moment at the hip and knee is a critical biomechanical strategy to enhance mobility in resource-constrained settings. PFFD, characterized by a shortened or absent proximal femur, results in significant biomechanical challenges, including reduced muscle power and joint stability (Aitken, 1969; Koman et al., 1982). The alternative coupled moment mechanism, as described, coordinates forces across the hip and knee joints in the sagittal or frontal plane to compensate for these deficits. This ap-proach aligns with principles outlined by Radcliffe (1955, 1970), who emphasized the importance of bio-mechanical alignment in prosthetic design to optimize joint function and minimize energy expenditure. By generating a coupled moment, the mechanism facilitates controlled hip and knee motion, enabling functional ambulation without reliance on complex, resource-intensive external operators like advanced prosthetics or surgical interventions, which may not be feasible in limited-resource environments (Seymour, 2006). This simple yet effective design is particularly beneficial for young patients, as it supports developmental mobili-ty needs while accommodating growth and limited physical parameters (Fixsen & Lloyd-Roberts, 1974).

The stability of the coxa and forward progression of the knee are pivotal for achieving functional gait in children with PFFD or similar conditions. The coupled moment stabilizes the hip by aligning forces to re-duce lateral deviations, a common issue in PFFD due to femoral shortening or absence (Panting & Williams, 1978). This stability is crucial for maintaining balance during ambulation, especially in young children who are still developing motor skills (Morris & Bartlett, 2004). The mechanism also promotes forward knee pro-gression, enabling a smoother gait cycle, which is consistent with Kaufman and Irby's (2006) findings on the role of orthotic and prosthetic designs in facilitating efficient movement. For a child under 8, this ap-proach minimizes the risk of compensatory movements that could lead to secondary musculoskeletal issues, a concern highlighted in studies of early PFFD management (Bryant & Epps, 1991). In resource-limited settings, where procedures like rotationplasty or advanced prosthetics (Torode & Gillespie, 1983; Oppen-heim et al., 1998) may not be accessible, this mechanism offers a practical alternative, ensuring functional mobility with minimal external support.

The multi-layer foot mechanism further enhances energy efficiency, a critical consideration for a young pa-tient with reduced physical capacity. This design, inspired by orthotic principles for energy storage and re-lease (Rose, 1986; Shurr & Michael, 2002), incorporates layered structures that absorb energy during the stance phase and release it during push-off, reducing the metabolic cost of walking. This is particularly ad-vantageous for children with PFFD, who often face increased energy demands due to biomechanical ineffi-ciencies (Koman et al., 1982). The mechanism's ability to reserve energy for consecutive steps supports sustained ambulation, aligning with Seymour's (2006) emphasis on designing prosthetics and orthoses that optimize function in lower-limb deficiencies. For a child in a resource-constrained environment, this ener-gy-efficient system is a viable alternative to complex prosthetic feet, which may be unavailable or impracti-cal (Razeghinezhad et al., 2021). By integrating these biomechanical adaptations, the overall approach pro-vides a functional, low-resource solution tailored to the developmental and physical needs of a young pa-tient.

Conclusion

The alternative coupled moment at the hip and knee serves as a critical biomechanical adaptation for a young patient under 8 years old with significant physical deficiencies and limited access to advanced external operators. This mechanism leverages coordinated forces in the sagittal or frontal plane to stabilize the coxa (hip) while facilitating forward progression of the knee. By integrating the hip and knee movements, the coupled moment compensates for reduced muscular strength or coordination, enabling more efficient locomotion despite the body's limitations. The design prioritizes simplicity and functionality, making it suitable for environments with constrained resources, ensuring that the patient can achieve basic mobility with minimal external support.

The stability of the coxa and forward progression of the knee are enhanced through this alternative mechanism, which strategically distributes forces to maintain balance and promote movement. The coupled moment acts to stabilize the hip joint by aligning forces in a way that reduces unwanted lateral or rotational deviations, critical for a child with compromised musculoskeletal capabilities. Simultaneously, it drives the knee forward during the gait cycle, supporting a smoother and more controlled stride. This dual action not only improves functional mobility but also minimizes energy expenditure, which is vital given the patient's reduced physical parameters and developmental stage.

The multi-layer foot mechanism further complements this system by optimizing energy storage and release during ambulation. This innovative design incorporates layered structures that absorb and conserve energy during the stance phase of walking, storing it for subsequent steps. By recycling a definitive amount of energy, the mechanism reduces the metabolic cost of movement, which is particularly beneficial for a young patient with limited stamina and resources. This energy-efficient approach supports consecutive steps, enhancing endurance and enabling sustained progression, making it an effective solution for improving mobility in resource-constrained settings.

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