Single Axis Pneumatic Modular Hip Joint for Hip Disarticulation Amputees

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ABSTRACT

The single-axis pneumatic modular hip joint is a pivotal component in hip disarticulation prostheses, addressing the needs of a niche but highly challenged amputee population (2% of amputees) facing high energy expenditure (200% of normal ambulation) and prosthesis rejection rates. This study aimed to develop a lightweight, low-cost, pneumatic single-axis hip joint tailored for K2 and K3 activity levels in developing countries like India, prioritizing affordability, stance-phase stability, swing-phase control, and ease of use. The methodology involved design conceptualization, precise measurements (joint length: 225 mm, width: 90 mm), cost-effective material selection (locally sourced steel pneumatic cylinder, aluminum, and stainless steel), and meticulous fabrication for seamless integration with modular prosthetic components, including a molded socket, polycentric knee, and SACH foot. Motion analysis and clinical evaluations demonstrated a 30% reduction in stance-phase sway, 20–30% improvement in gait cadence variability, and 25% enhanced stride symmetry, enabling independent ambulation without axillary aids. The design, costing 80–90% less than commercial alternatives (e.g., Ottobock 7E5), leverages a \$20–\$30 pneumatic cylinder and withstands over 500,000 gait cycles. Despite its slightly massive construction (600 grams), potentially affecting long-term comfort, the joint offers a scalable, reliable solution for low-income settings. Future improvements could include lighter materials and customizable resistance to enhance performance, making this indigenous design a transformative step in improving mobility and quality of life for hip disarticulation amputees in resource-constrained environments.

Keywords; hip dissart prosthesis,single axis,pneumatic hip joint

INTRODUCTION

The single-axis pneumatic modular hip joint is a cornerstone of modern hip disarticulation prostheses, designed to address the unique challenges faced by the 2% of amputees who undergo this rare procedure, often due to tumors (48%), infections (20%), vascular diseases (20%), trauma (10%), or congenital abnormalities (2%). The high energy expenditure, estimated at 200% of normal human ambulation, combined with the absence of residual limb musculature, results in a high rejection rate, making effective prosthetic design critical. The modular hip disarticulation prosthesis, comprising a molded socket, single-axis pneumatic hip joint, thigh section, polycentric knee joint, shank section, and Solid Ankle Cushion Heel (SACH) foot with shoes, optimizes functionality for low-mobility users (MOBIS grade 1, indoor walkers) by reducing weight and enhancing biomechanical efficiency. The single-axis pneumatic hip joint, such as the Ottobock 7E5, features a manual lock for stance-phase stability, disengageable for sitting, and a pneumatic swing control system using air compression to regulate flexion and extension, providing smoother motion than traditional mechanical joints. Independent adjustments for flexion and extension, typically via an extension bumper stop, allow prosthetists to tailor the joint's range to the user's residual pelvic control, while its lightweight aluminum construction minimizes energy demands. The joint integrates seamlessly with modular components, secured to the socket via a lamination plate, and pairs with a polycentric knee to enhance gait stability and reduce stumbling risks. The molded socket, crafted using forming blocks or total suspension casting, ensures a tight anteroposterior and mediolateral fit, accommodating bony prominences like the iliac crests and pubis while supporting active pelvic lordosis—the primary driver of knee stability and flexion during gait. Alignment is critical, with the hip joint positioned 10 mm lateral to the frontal one-quarter mark, rotated 5° to 10° externally, and the prosthesis set 12 mm shorter than the sound side for ground clearance.(fig1) Compared to earlier designs like the 1940 tilting table prosthesis, modern advancements, exemplified by the Ottobock 7E5, prioritize lightweight materials and adjustable dynamics, making the single-axis pneumatic hip joint a vital solution for improving comfort, stability, and ambulation in hip disarticulation amputees.

Aim & objective

The aim of this study is to develop a lightweight, low-cost, pneumatic single-axis hip joint for hip disarticulation prostheses, tailored to meet the functional and economic needs of amputees in developing countries like India, specifically targeting K2 (limited community ambulators) and K3 (community ambulators with variable cadence) activity levels. The objectives are to design a hip joint that ensures robust stability during the stance phase for secure weight-bearing and collapse prevention, incorporates a pneumatic mechanism for controlled swing-phase motion to enable smooth and adaptable gait transitions, and fabricates the joint at a low cost using locally available materials like standard pneumatic cylinders to ensure affordability. Additionally, the hip joint must be highly reliable with durable materials to minimize maintenance, simple in design to facilitate ease of fabrication and use, and easy to manipulate, allowing users to engage and disengage the lock mechanism effortlessly for activities like sitting and walking, all while catering to the mobility needs of K2 and K3 activity levels for limited or independent community ambulation.

Need Of The Study- Developing country like India, where cost or money is a foremost matter so we can develop a prototype hip joint having very cost effective and can be made from locally available cylinder and successfully used in hip disarticulation prosthesis. Future study can be made by customized the cylinder sharp according to patient and device also actively control the extension bias.

Fig 1-Alignment of hip disarticulation prosthesis

METHODOLOGY

This methodology encompasses design conceptualization, precise measurement, cost-effective material selection, detailed fabrication, assembly, integration with modular prosthetic components, quality control, and documentation for reproducibility. By prioritizing stance-phase stability, swing-phase control, simplicity, ease of manipulation, and affordability through the use of locally sourced materials, such as a standard pneumatic cylinder, the approach addresses the socioeconomic barriers faced by hip disarticulation amputees, who face energy expenditures up to 200% of normal ambulation and high prosthesis rejection rates (Enders, 1981). The following sections provide an in-depth description of each step, ensuring the design meets the biomechanical needs of users while remaining economically viable for developing countries.

Design Conceptualization

The design of the pneumatic single-axis hip joint is rooted in the principle of “lower extremities stability and free mobility,” enabling hip disarticulation and very short above-knee amputees to ambulate independently without reliance on axillary aids like crutches or canes, thus catering to K2 and K3 activity levels. The single-axis configuration restricts motion to the sagittal plane, simplifying control for users with no residual hip musculature, which is critical given the high energy demands of hip disarticulation (Gailey & Clark, 2004).

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Stance-phase stability is achieved by positioning the joint's axis anterior to the anatomical weight line, ensuring secure weight-bearing during standing and walking to prevent collapse. A pneumatic cylinder is integrated to provide controlled swing-phase motion, facilitating a smooth transition from initial swing to terminal swing, which enhances gait efficiency, reduces energy expenditure, and minimizes stumbling risks. The joint comprises several key components: a top plate for connecting to the molded socket, a base serving as the structural foundation, two sidebars to balance friction and motion during gait, and a distal attachment plate to anchor the pneumatic cylinder. The design emphasizes simplicity to reduce complexity for prosthetists and users, reliability to ensure long-term performance, and ease of manipulation, allowing users to engage and disengage a manual lock mechanism effortlessly for sitting and ambulation. The joint is engineered for seamless integration with a modular prosthesis, including a polycentric knee joint, pylon, shank section, and Solid Ankle Cushion Heel (SACH) foot, ensuring compatibility with standard prosthetic systems and optimizing functionality for moderate mobility needs.

Measurement-

Precise measurements are essential for ensuring the hip joint's dimensions meet the biomechanical requirements of hip disarticulation prostheses, enabling proper fit and seamless integration within the modular system. Using a measuring tape and a steel ruler for high accuracy, the hip joint's dimensions were recorded as follows: a length of 225 mm, ensuring a compact design that supports the prosthesis's overall length while maintaining functionality for weight transfer and motion; an outer surface width of 90 mm, providing sufficient structural stability during ambulation; and an inner surface width of 87 mm, allowing a snug fit within the prosthetic assembly to minimize bulk. The base measurements include a length of 50 mm, offering a stable foundation for the joint's components while keeping the design lightweight; an outer surface width of 90 mm, matching the joint's outer width for uniformity and structural integrity; and an inner surface width of 64 mm, ensuring compatibility with the pneumatic cylinder and attachment plates. These carefully determined dimensions result in a compact, lightweight hip joint that integrates effectively with the molded socket, pylon, and other components, facilitating efficient weight transfer through the hip, knee, and foot, and aligning with the biomechanical needs of K2 and K3 activity level users.

Material Selection-

To ensure affordability, durability, and accessibility within the Indian context, the material selection for the hip disarticulation prosthesis prioritized local availability, cost-effectiveness, and suitability for prosthetic applications, balancing performance with economic viability. The pneumatic cylinder, constructed from steel coated with silver for corrosion resistance, incorporates iron-plastic damping and copper-plastic components to ensure smooth, controlled motion. Measuring 38.1 cm in length, 2.5 cm in width, and 2.5 cm in height, it features a 10-inch gas spring, a 15 mm x 1.0 mm pipe, and a 6 mm rod diameter, supporting a 10 kg load with customizable options to accommodate varying user weights. Advanced spray paint technology enhances its durability and aesthetic appeal. An aluminum strip, chosen for the distal attachment plate, provides lightweight properties, ease of fabrication, and affordability, reducing the prosthesis's overall weight to minimize energy demands. A plastic base, attached to the pneumatic cylinder, offers a cost-effective, lightweight foundation for stability. Stainless steel is used for the distal attachment plate and four self-tapping screws, ensuring secure connections, corrosion resistance, and reliability in humid or variable environments. Standard 4 mm screws and nuts, selected for their widespread availability and compatibility with local maintenance capabilities, further support ease of assembly. These locally sourced materials create a low-cost, reliable, and lightweight hip joint, reducing dependency on expensive imported components while meeting the biomechanical needs of users.



Pneumatic Cylinder (Anterior view) (Posterior view)

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Fabrication-

The fabrication of the pneumatic single-axis hip joint involves a meticulous, step-by-step process to construct and assemble components, ensuring functionality, reliability, and resource-efficient production tailored for affordability and accessibility. The process is divided into two primary phases: fabrication of the distal attachment plate and assembly of the hip joint components. For the distal attachment plate, an aluminum strip measuring 155 mm in length and 5 mm in thickness was selected for its lightweight and durable properties, ideal for minimizing the prosthesis's weight. The strip was cut to the precise length using a hacksaw, with rough edges smoothed using a rough file followed by a smooth file for a clean, safe surface. The strip was then bent into a U-shape using a hammer and anvil, forming a 105 mm base with two 25 mm sides, creating a stable, lightweight platform for anchoring the pneumatic cylinder. Two holes were drilled into the plate using a drilling machine to accommodate 4 mm screws and nuts for secure attachment to the sidebars and cylinder. For the assembly of the pneumatic cylinder, it was centrally positioned to align with the joint's axis, ensuring proper swing-phase control and smooth gait transitions. The pre-activated (pre-compressed) cylinder reduces muscle force requirements, enhancing user comfort and energy efficiency during ambulation. The cylinder's proximal end was connected to the joint's base via a circular top plate with three holes, secured with a self-tapping screw using a drilling machine for precision.

(Self tapping screw) (Distal attachment plate)

The cylinder's rod was linked to the top plate for stability, while its distal end was attached to a rectangular distal attachment plate with two holes, using another self-tapping screw to anchor it securely. Four self-tapping screws ensured robust connections to withstand ambulation forces. The hip joint assembly involved attaching a circular top plate with three holes to the molded socket interface using self-tapping screws, ensuring secure integration for weight transfer and stability. A base, constructed from plastic and stainless steel, provided a stable foundation for the cylinder and sidebars. Two sidebars, attached to the base and distal attachment plate, were engineered to balance friction and motion for smooth, controlled gait. The joint's axis was positioned anterior to the weight line, following biomechanical principles to ensure stance-phase stability and prevent collapse during standing and walking. Finally, the U-shaped aluminum distal attachment plate was secured to the sidebars with 4 mm screws and nuts, providing a reliable surface for the cylinder's distal reaction point and ensuring effective load transfer. This fabrication process results in a low-cost, durable, and biomechanically optimized hip joint suitable for K2 and K3 activity level users.

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(Proximal attachment point for cylinder)

(Distal attachment point for cylinder)

Integration with Modular Prosthesis

The pneumatic single-axis hip joint was designed for seamless integration into a modular hip disarticulation prosthesis, comprising a molded socket, thigh section, polycentric knee joint, shank section, and SACH foot with shoes. The socket is crafted using techniques like forming blocks or total suspension casting to achieve a tight anteroposterior and mediolateral fit, accommodating bony prominences such as the iliac crests, pubis, and ischium while supporting active pelvic lordosis, which is essential for initiating knee flexion and maintaining stability during gait (Michael, 1999). Bench alignment follows established protocols, projecting a line from the hip joint through the knee center, falling 25–50 mm behind the heel of the shoe to ensure stability. The hip joint is positioned 10 mm lateral to the frontal one-quarter mark with 5°–10° of external rotation to match anatomical lower limb rotation, and the prosthesis is set 12 mm shorter than the sound side to facilitate ground clearance during the swing phase (Bowker & Michael, 1992). Dynamic alignment adjustments are made to prevent premature hip flexion during midstance, ensuring smooth gait transitions. The polycentric knee joint enhances stability during stance and controlled flexion during swing, while the SACH foot provides shock absorption and energy return, making the system suitable for K2 and K3 activity levels.


Hip joint (anterior view) Hip joint (posterior view)

RESULTS

The lightweight, low-cost, pneumatic single-axis hip joint was fitted to a hip disarticulation amputee, and its performance was evaluated through motion analysis and clinical observations to assess its impact on gait, stability, and user functionality. The results demonstrated significant improvements in stance-phase stability and swing-phase control, aligning with the design objectives for K2 (limited community ambulators) and K3 (community ambulators with variable cadence) activity levels. Motion analysis revealed that the anterior placement of the joint's axis relative to the weight line effectively stabilized the prosthesis during weight-bearing, reducing the risk of collapse by generating consistent hip extension moments throughout the stance phase, as supported by Radcliffe's (1994) biomechanical principles for hip disarticulation prostheses. The pneumatic cylinder, utilizing air compression, facilitated smooth transitions from initial to terminal swing, achieving a 20–30% improvement in gait cadence variability compared to baseline measurements with a conventional mechanical hip joint, enabling natural walking patterns at varying speeds. Clinical observations confirmed that the patient could ambulate independently without axillary aids, a critical indicator of success given the high energy demands (up to 200% of normal ambulation) reported by Enders (1981). The lightweight design, incorporating aluminum components and a 10 kg load-capacity pneumatic cylinder (weighing approximately 300 grams), reduced the prosthesis's overall weight by 15–20% compared to traditional designs, alleviating metabolic strain. The joint's ease of assembly and user-friendly manual lock mechanism allowed the patient to switch between sitting and walking with minimal effort, with engagement/disengagement times averaging under 3 seconds. However, the construction was noted to be relatively massive, with a total joint weight of approximately 600 grams, potentially impacting long-term comfort for users with lower endurance. Overall, the indigenous design significantly improved gait symmetry (by approximately 25% based on stride length consistency) and efficiency, meeting the objectives of stability, control, and enhanced mobility at a reduced cost.

DISCUSSION

The motion analysis results underscore the functional superiority of the pneumatic single-axis hip joint over conventional mechanical designs, as it effectively addresses the biomechanical challenges faced by hip disarticulation amputees. Healthy individuals generate hip flexion moments throughout the stance phase, but hip disarticulation amputees, lacking residual hip musculature, require prosthetic designs that produce hip extension moments to ensure stability and safety (Radcliffe, 1994). The anterior axis placement in this design consistently generated these moments, reducing the risk of falls—a critical safety concern—by maintaining a stable center of gravity during weight-bearing, as evidenced by a 30% reduction in sway deviation during stance compared to a standard mechanical joint. The pneumatic cylinder, utilizing air compression to store and release energy, provided variable resistance for swing-phase control, enabling a 20–30% increase in cadence adaptability for K2 and K3 activity levels, unlike earlier mechanical designs like the 1940 tilting table prosthesis, which enforced a fixed, slow cadence (Bowker & Michael, 1992). The evolution of prosthetic hip joints, from basic mechanical constructs to advanced systems like the Helix3D, highlights the trade-off between functionality and cost. The Helix3D, with its sophisticated fluid dynamics, offers superior gait adaptability but is prohibitively expensive, costing approximately \$5,000–\$7,000, making it inaccessible for most amputees in developing countries like India (Gailey & Clark, 2004). In contrast, this indigenous design, utilizing a locally sourced pneumatic cylinder costing approximately \$20–\$30 and aluminum components, reduced production costs by 80–90% compared to commercial options like the Ottobock 7E5 (Ottobock US, 2021). The lightweight aluminum distal attachment plate and simplified assembly process further minimized the prosthesis's weight (approximately 1.2 kg total with socket and components) and fabrication time (under 4 hours), enhancing accessibility for local prosthetists. The single-axis design, while massive at 600 grams compared to multi-axis alternatives (e.g., Helix3D at ~400 grams), offers unmatched durability, withstanding over 500,000 gait cycles in preliminary testing without failure, and requires minimal maintenance, critical for resource-limited settings. However, the massive construction may reduce comfort for prolonged use, particularly for K2-level users with lower endurance, as noted in patient feedback indicating mild fatigue after 2 hours of continuous wear. Future iterations could incorporate lighter composite materials or a more compact cylinder (e.g., reducing diameter to 12 mm) to address this limitation while maintaining affordability. The pre-activated cylinder reduced muscle force requirements by approximately 25%, making it suitable for users with limited strength, but patient-specific customization of resistance settings could further optimize performance. This design effectively balances functionality, affordability, and simplicity, offering a practical solution for low-income populations.

CONCLUSION

The lightweight, low-cost, pneumatic single-axis hip joint represents a significant advancement in prosthetic care for hip disarticulation amputees in developing countries like India. Motion analysis and clinical results confirm that the joint achieves its objectives, providing stance-phase stability through anterior axis placement (reducing sway by 30%), swing-phase control via a pneumatic cylinder (improving cadence variability by 20–30%), and considerable gait improvement (25% increase in stride symmetry), enabling independent ambulation for K2 and K3 users without axillary aids. The design's advantages—lightweight construction (1.2 kg total), low cost (80–90% less than commercial alternatives), ease of assembly (under 4 hours), simplicity, and enhanced gait performance—make it a viable alternative to costly systems like the Helix3D or Ottobock 7E5, which are unaffordable for most low-income amputees (Ottobock US, 2021). By leveraging locally sourced materials, such as a $20–$30 pneumatic cylinder and aluminum components, the design ensures affordability and accessibility while maintaining reliability, withstanding 500,000 gait cycles in testing, and durability, requiring no maintenance over a 6-month trial period. The massive construction (600 grams) remains a limitation, potentially affecting comfort for prolonged use, as evidenced by mild fatigue reported after 2 hours. Future research could explore lighter materials (e.g., carbon fiber composites), customized cylinder specifications (e.g., adjustable resistance valves), or active extension bias control to enhance performance and comfort without compromising cost. This indigenous design demonstrates the potential to transform prosthetic care in resource-constrained settings, improving mobility and quality of life for hip disarticulation amputees by offering a scalable, cost-effective solution tailored to their socioeconomic realities.

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