



International Journal of Computational Biology and Drug Design

ISSN online: 1756-0764 - ISSN print: 1756-0756

<https://www.inderscience.com/ijcbdd>

Innovating prosthetic foot design: integrating big data and computational biology for enhanced lower limb rehabilitation

Sushree Sangita Nayak, Aswini Kumar Mohapatra, Srikanta Maharana, Bijay Kumar Paikaray

DOI: [10.1504/IJCBDD.2025.10069522](https://doi.org/10.1504/IJCBDD.2025.10069522)

Article History:

Received:	17 October 2024
Last revised:	10 December 2024
Accepted:	27 December 2024
Published online:	09 May 2025

Innovating prosthetic foot design: integrating big data and computational biology for enhanced lower limb rehabilitation

Sushree Sangita Nayak

Department of Prosthetics and Orthotics,
SVNIRTAR,
Odisha, 754010, India
Email: lollybpo@gmail.com

Aswini Kumar Mohapatra

CIPET,
Odisha, 751010, India
Email: draswinikumarmohapatra@gmail.com

Srikanta Maharana

Department of Prosthetics and Orthotics,
SVNIRTAR,
Odisha, 754010, India
Email: srikantmoharana2012@gmail.com

Bijay Kumar Paikaray*

Centre for Data Science,
Department of Computer Science and Engineering,
Siksha 'O' Anusandhan (Deemed to be) University,
Bhubaneswar, Odisha, 751003, India
Email: bijaypaikaray87@gmail.com

*Corresponding author

Abstract: This paper aims to discover in-depth knowledge of the design technology, material used, and clinical use of dynamic response prosthetic feet in rehabilitating lower limb amputees. Studies were done using electronic databases such as PubMed, Google Scholar, SCOPUS, and Research Network 2010–2024. Out of 162 papers, 43 papers relevant studies were included. Significant advances in the research and development of prosthetic legs over the last two decades have improved the functioning and quality of life of many lower-limb amputees living in industrialised countries. The disadvantage of this new RandD is that most end users live in developing countries and cannot benefit from this new technology due to the cost, durability, maintenance, and availability of these components. Research is needed to design and develop cost-effective prosthetic legs that meet economic, environmental, and physical standards and withstand adverse climatic and working conditions.

Keywords: foot design; finite element analysis; rehabilitation; big data.

Reference to this paper should be made as follows: Nayak, S.S., Mohapatra, A.K., Maharana, S. and Paikaray, B.K. (2025) 'Innovating prosthetic foot design: integrating big data and computational biology for enhanced lower limb rehabilitation', *Int. J. Computational Biology and Drug Design*, Vol. 16, No. 3, pp.281–299.

Biographical notes: Sushree Sangita Nayak is currently working as demonstrators in prosthetic and orthotics at SVNIRTAR. She is pursuing her PhD. At CIPET, Bhubaneswar in Material Science. She has more than 10 years of teaching and clinical experience in P&O field. She has presented more the 20 scientific papers in both national and international journal.

Aswini Kumar Mohapatra, Principal Director, CIPET is a Front Line Scientist and Mentor in the field of Plastic Engineering and Material Development. His contribution in the field of engineering is accepted nation wise for reduction of casting and enhancement of quality. He has an incarnation towards human life and he himself emerges in the research and development program towards development of quality of life. As a result, he is associated with NIRTAR for discovering cost-effective quality material for the cause of disability towards quality of materials for quality of living.

Srikanta Maharana is currently working as HOD, DPO at SVNIRTAR. He has published more than 35 years of experience. He has published more than 20 papers in both national and international index journal. He has presented more than 60 scientific papers in national and international conferences. He has vast clinical knowledge in fitting of complicated cases.

Bijay Kumar Paikaray currently serves as an Associate Professor at the Centre for Data Science, Department of Computer Science and Engineering, Siksha 'O' Anusandhan (Deemed to be) University, Odisha, India. He earned his PhD and MTech in Computer Science and Engineering from Centurion University, Odisha, India. With 16 years of robust academic experience, he is deeply committed to both teaching and research. In addition to teaching, he has authored more than 50 research publications, holds patents, and has authored books. His research interests include information security, machine learning, data visualisation, and IoT.

1 Introduction

According to the latest census about 1.8% of the total population comprise of disabled persons in India. In India there are more than 70 lakh amputees and to this figure about 30,000 new amputees are added annually. Locomotors disability accounts for about 106.34 lakhs of the total population out of which Lower limb amputee accounts to a major portion of the amputee population. Out of the many parameters for getting high success in lower limb rehabilitation advancement in material fabrication procedure are cardinal factors. However in low economic countries like India both these areas are lacking behind.

In lower extremity prostheses, Foot is the integral parts of the prosthetic system that contributes to successful installation and results. The main demand for dynamic response

foot in India is affordable price, light weight and high strength (Johnson et al., 2023). Currently, a large number of foot world market and the technology are developing. With the current prosthesis, the foot has gone through a huge change in both design and materials used (Johnson et al., 2023). Prosthetic feet that can store and release energy during walking may benefit lower limb amputees. Current foot prostheses differ from the materials and construction models routinely used in clinical use. A properly fitted foot can improve the comfort and performance of a prosthetic limb (Johnson et al., 2023).

The aim of this study was to summarise the literature on design, modelling, materials used and their impact on user satisfaction.

2 Literature review

Bates et al.' (2020) main goal was to describe recent technological advances that bring us one step closer to the goal of creating prosthetics that are multifunctional, self-identifying, durable, and intuitive. New technologies move by surgeon, rehabilitation doctor, therapist, and prosthesis, which is close to the purpose of creating a very functional prosthetic product with sensory control. The cooperation between medical teams, scientists, and industry stakeholders must obey patients who need powerful and high prostheses.

Diyaa (2022) studied a novel dynamic prosthetic foot with energy storage and release capabilities, which will be developed using a composite material consisting of carbon fibre laminated with resin. The mechanical properties and S-N curve of the composite material were experimentally calculated by testing samples consisting of resin laminated carbon fibres. These characteristics are then fed into a digital solution using ANSYS software to design the proposed prosthesis, with multiple trials to achieve a good result that meets the desired goals. Along with knowledge of the mass and volume of the foot, the results are calculated, as indicated by the equivalent stress, directional strain, number of fatigue cycles and safety factor.

Koehler-McNicholas et al. (2018) compares the mechanical properties (e.g., forefoot stiffness) and dynamic functions (e.g., swing radius, effective aspect ratio of the foot, and energy return at end of support) of prosthetic feet designed for highly active users. Load-deflection curves were obtained for nine ankle prosthetic systems using a servo hydraulic test frame and load cell. Effective roll shape characteristics and late stance energy return values were then obtained using quantitative gait analysis for three users with unilateral transtibial amputations. Mechanical and dynamic testing showed that although forefoot stiffness varied across the nine feet examined in this study, the measured changes in rollover foam radius and effective foot length ratio were relatively weakly responsive to weighted walking. Mechanical and dynamic testing showed that although forefoot stiffness varied across the nine feet examined in this study, the measured changes in rollover foam radius and effective foot length ratio were relatively weakly responsive to weighted walking.

Li et al. (2024) conducted a study on the partial mechanical model of the prosthetic foot during stance phase, and the optimal dimensions and driving forces of the prosthetic foot structure were used to obtain the prosthetic foot structure parameters. In addition, a carbon fibre energy storage foot was designed based on the profile of the human foot, and the dynamic response of the elastic strain energy at different thicknesses was simulated and analysed. Finally, we integrated bionic ankle-foot prosthesis and

experiments were conducted to verify the bionic nature of the prosthetic joint motion and the energy-storage characteristics of the carbon fibre prosthetic foot. The proposed ankle–foot prosthesis provides ambulation support to assist amputees in returning to social life normally and has the potential to help improve clinical viability to reduce medical rehabilitation costs.

Higher numerical stiffness categories resulted in increased axial stiffness values in the heel, midfoot, and forefoot, increased plantar flexion and dorsiflexion stiffness values, and decreased hysteresis in the heel, midfoot, and forefoot. Furthermore, in this category, increasing prosthetic foot size resulted in decreased axial stiffness values in the heel, midfoot, and forefoot, increased plantar flexion and dorsiflexion torsional stiffness values, and decreased hysteresis in the heel and midfoot. Furthermore, the addition of a shoe to the prosthesis decreased axial stiffness values in the heel and midfoot, decreased plantar flexion torsional stiffness values, and increased hysteresis in the heel, midfoot, and forefoot.

Abdulradi et al. (2024) In particular, when it comes to prosthetic feet, the choice of prosthesis depends on how well it imitates the features of the human foot. Prosthetic feet are made to be flexible, durable, corrosion-resistant, tear-resistant, rust-resistant, shear-resistant and cost-effective. If the composite material is changed from the viewpoint of selection of fibre, system, combination, mass capacity, and prosthetic architecture, the efficiency of the foot changes. In this paper, a detailed investigation of biomechanics, elements, and ideas of artificial foot was conducted.

3 Methods

3.1 Literature search

Apply EBSCO, Emerald, ProQuest, PubMed and Web of Science were searched for relevant literature from 1st January, 2010 to 31st March, 2023. 162 scientific papers were found. The search used the following keywords, their variations and combinations: prosthesis, lower limb, amputation, dynamic response, energy storage, leg prosthesis.

3.2 Criterion

Peer-reviewed papers in English dealing with foot design, computer modelling, finite element analysis and simulation were selected. Before starting the study; we defined the basis and methods of the review in the protocol. The observation period was from 2010 to March 2023 (13 years).

3.3 Study selection

The following topics were selected for research:

- 1 material used in foot
- 2 design, modelling, analysis of prostheses with dynamic response
- 3 clinical applications in lower limb amputee's rehabilitation.

It helps to understand how the technological development of dynamic responsive leg prostheses provides clinical prosthetic rehabilitation for patients with tibial or Trans femoral amputation.

3.4 Inclusion criteria were established for the selection of papers

- a Based on innovation, Clinical analysis study design, ranging from a complex randomised controlled trial (RCT) to a simple case study.
- b Both trans-tibial and Trans femoral amputee.
- c Study of dynamic response foot and its comparison with counterparts.

3.5 Data extraction

Papers were excluded when any of the inclusion criteria were not met – Reference management software EndNote (version X6, Thomson Reuters; Philadelphia, Pennsylvania) was used for resulting references. Duplicate references have been removed. The remaining papers were provisionally classified as intervention studies (clinical studies) or special studies. Reviewers independently screened references and classified them as

- 1 relevant
- 2 irrelevant
- 3 uncertain given inclusion and exclusion criteria.

All citations classified as significant or uncertain were screened from full-text papers. The meaning of the uncertain references was clarified in conversation with two other reviewers. Review of full texts and appropriate discussion led to group consensus and final inclusion or exclusion.

Data collection process: A data extraction table (Koehler-McNicholas et al., 2018) (Appendix 2, available online only) was prepared for this review using the Cochrane Collection Form for Non-Randomised Trials. Relevant data were extracted from the included studies and summary tables were prepared for each study. Information on study type, study objective(s), participants, inclusion and exclusion criteria, outcome measures, main results, findings and conclusions were included. Data were collected by the first author and then reviewed by the second author.

SCORE: The search yielded 162 research abstracts. After applying the inclusion and exclusion criteria, a total of 43 studies were included in the systematic review.

4 Materials used in the dynamic response foot

It is important to note that the materials used in prosthetic foot can vary greatly depending on the design, the intended level of performance and the individual requirements of the wearer. Each prosthetic foot is customised according to the needs and preferences of the prosthetic wearer. These aspects depend both design and manufacture of the foot and mechanical properties of the material (Walke and Pandure, 2017).

Especially those designed for active individuals and athletes, often incorporate various materials to mimic the natural biomechanics of the human foot. Some common materials used in dynamic response prosthetic feet include: Carbon Fibre, EVA (Ethylene-vinyl acetate) Foam, Polyurethane, Kevlar, Rubber, springs or Hydraulics (Walke and Pandure, 2017).

4.1 Use of dynamic responsive prosthetic legs in developing countries

The use of dynamic response foot in developing countries can have a positive impact on lower limb amputees. Dynamic response feet are designed to mimic the natural movement of the human foot, making walking smoother and more energy efficient. They can be particularly useful in developing countries for the following reasons:

Cost-Effectiveness, Increased Mobility, Enhanced Productivity, Reduced Health Issues, Customisation Options, Improved Prosthetic Acceptance, Capacity Building and Local Expertise, Social Integration.

Despite these advantages, widespread use of foot movements in developing countries remains challenging. These include limited access to prosthetic technology, a shortage of professional prosthetists, and financial constraints. NGOs, governments, and international organisations can play an important role in overcoming these challenges by supporting projects to provide quality materials, providing local specialised training for professionals, and supporting research and development in this area.

4.2 Dynamic prosthetics foots in developed countries

Dynamic prosthetics are a breakthrough in prosthetics, providing users with more natural walking and improved mobility. These prosthetics are designed to mimic the function of a normal foot, adapting to terrain changes and providing a smoother, more energy-efficient gait.

In developed countries, the use of dynamic response prosthetic feet has become increasingly common and beneficial for amputees for several reasons: Enhanced Mobility, Improved Quality of Life, Reduced Strain and Fatigue, Enhanced Prosthetic Technology, research and development in the field, Customisation and Personalisation.

4.3 Energy storing feet market

The market of lower limb prostheses offers leg prostheses for all activity levels (K – the 4-level functional classification system of the lower limb amputation agent and the medical necessity of certain prosthetic components). Each K level corresponds to the performance range of a foot. We distinguish between normal legs (SACH, uniaxial and multiaxial) for people with limited mobility and energy-saving legs for active people. It shows the foot prosthetic models offered by three selected leading prosthetic manufacturing Table 2 companies (RRF, Otto Bock, Ossur) and their manufacturing material (Kadhim Oleiwi and Namah Hadi, 2016; Talla et al., 2021; Kadhim, 2022; Tarrade et al., 2021). Table 1 Examples of selected foot models, their effectiveness and the material they are made of.

Table 1 Mechanical properties of materials used in prosthetic foot

<i>Material</i>	<i>Tensile strength (MPa)</i>	<i>Young's modulus (GPa)</i>	<i>density(g/cm³)</i>	<i>Poisson's ratio</i>
Carbon fibre	3800	230	1.4	0.2
Polypropylene	31–45	36–40	0.90–0.91 (0.905)	0.40–45
Reinforced carbon fibre	110	200–500	1.8–2	0.7
Fibre glass	3450	72.5	2.48	0.23
PMMA	53.8	2.5	1.19	0.38
Kevlar	2900–3450	59–179	1.44–1.47	
UHMWPE	2900	114.86	0.939	0.4
Perlon	78	3.43	1.083	0.39
Glass	1350–4900	60–90	2.5–2.6	
Polyester	45–85	1.3–4.5	1.1–1.4	
Epoxy	40–85	2.1–5.5	1.2–1.4	
Glass fibres/polyester	1250	48	2.0	
Carbon fibres/epoxy	1050	180	1.5	
Aramid/epoxy	1250	76	1.4	
Steel	1000	200	7.8	

Table 2 Material used in prosthetic foot

Khafidh et al. (2023)	Mechanical properties of elastomeric materials for foot prostheses: a comparison of local and imported products	To test the elastomer mechanical properties of foot prosthetic material, three types are used: import A, import B and local C. Prosthetic leg products were tested according to the following test parameters:	The hardness of the imported product A is higher than that of the local C, while the hardness of the local C and that of the imported product B are similar. The highest results are obtained from the tensile stress and the elongation at the break of local C	Import product A shows the highest hardness. Local C and import product B show similar hardness. However, the tensile stress at break and elongation of local C shows the highest results
		Density		
		Hardness		
		Tension		
		Tear		
		Compression		
		Local C is twice the density of imported A and		
Hadi and Olewi (2015)	Improving Tensile Strength of Polymer Blends as Prosthetic Foot Material Reinforcement by Carbon Fibre	In this study, we developed a new polymer compound, self-healing PMMA/SR that can be used in the production of prosthetic legs at an affordable price and with excellent performance	Polymer blend application was one of the easiest ways to determine the tensile strength of polymer blends	When CF is used as a reinforcement material, its tensile strength is high, resulting in a higher tensile strength for polymer blends, resulting in an increase in tensile strength as well as elastic modulus

Table 2 Material used in prosthetic foot (continued)

Hadi and Oleiwi (2015)	Improve Flexural Strength of PMMA/SR Polymer Blend by Reinforcement with Carbon Fibres as Prosthetic Foot Polymer Material	Polymer composites have advanced significantly in recent years and are now widely used in many orthopaedic and prosthetic applications	In the study, PMMA/SR reinforcement with CF blends were developed as prosthetic legs material. PMMA has great flexural properties and is a good polymer mix for this application	As the reinforcement material increases, so does the flexural strength and the flexural modulus. The five polymer blends increase in flexural strength and improve as the best comparable foot prosthesis material
Almuslehi (2014)	Development of New Composite Materials for the Foot Prosthetics Industry	This paper discusses the development of two kinds of composite materials that are suitable for the production of prostheses at affordable prices and with good mechanical properties	For example, the Young's modulus for 40% HDPE (High Density Polyethylene) filled by 60% PDW (Palm Wood) increases to 80% as compared to HDPE (Pure)	In addition, yield and final stresses was about 2×s higher than HDPE, and maximum elongation (MEL) and impact energy (EI) were significantly reduced
Hussain (2017)	Mechanical properties of hybrid and polymer matrix composites used in the manufacture of partial foot prosthesis	Polypropylene, polyethylene, and composite materials (perlon-carbon, Perlon and carbon-fibre-glass fibre hybrid) were tested experimentally	The samples were tested according to the following test procedures (Tensile Testing, Flexural Testing and Fatigue Testing): All tests were performed at room temperature Composite materials exhibit a high degree of increased mechanical properties	Hybrid carbon fibre, on the other hand, has a higher proportion of glass fibre compared to polypropylene (PPE) or polyethylene (PPE). Fatigue life has also been significantly improved for both Perlon carbon-perlon and Hybrid Carbon fibreglass
Sehar (2022)	Effect of laminations on the mechanical strength of carbon fibre composites in the manufacture of foot prostheses	Low tensile strength, low impact resistance, high price, and weight structure are some of the drawbacks of composite-based foot for lower limb amputations.	The objective of the study is to determine the tensile strength of carbon fibres laminate with varying amounts of carbon fibres laminates	Increasing the number of carbon layers in subsequent samples increased the tensile strength of the carbon fibre laminate
Mohammed (2020)1	Design and modelling of a foot from suitable composite materials	This work deals with the development of a composite material that can be used to make prostheses with reasonable costs and mechanical properties	When filled with 40% HDPE (high density polyethylene) + 60% PDW (palm wood), the Young's modulus increases from 40% to 80%, resulting in improved performance and ultimate stresses	As a general rule, an articulated foot costs about 60% less than a non-articulated one. The price and weight of this type of foot are the same as those of the standard SACH foot.

Table 2 Material used in prosthetic foot (continued)

Kelechi et al. (2020)	Biomechanical properties of rattan in the design and manufacture of foot	In the design of amputee prostheses, tension, bending, stretching and compression of the device, as well as the distribution of energy during the applied load was measured	Four types of dry rattan rod were examined for their biomechanical characteristics. Sampling 3 had the highest tensile strength at 11.5 N/mm ²	Sample 3 has the highest load resistance at 8.79 MPa. Sample 4 has the highest compressive strength at 9.94 MPa. The applied modulus at break load at 309 N is 283.14 MPa
Ismail et al. (2021)	Mechanical Properties of Carbon Matrix Composites in Blade Runner Artificial Foot	A fibre yielding composite is a composite of different polymer resins. It has a higher strength-to-weight ratio and better biocompatibility compared to monolithic materials. The objective of this study was to study a monolithic composite of glassy carbon fibre with different matrix combinations for blades running prosthesis	Polymer matrices (ER, CR, OR, PR) were chosen based on their mechanical and physical properties	A blade runner's artificial leg can be made of carbon fibre or epoxy matrices, which absorb energy better under impact loads.
Talla (2022)	Study the Effect of Reinforcing Kevlar Fibres with Carbon Fibres and Glass Fibres on the Performance of the Athletic Prosthetic Foot	The mechanical properties of sports foot prosthesis were investigated from experimental, theoretical and numerical aspects to obtain sports foot prostheses	Six different fibre-reinforced (Kevlar, carbon, glass and perlon) composite laminates, consisting of matrix orthocrylic lamination 80:20 pro, were prepared	Young's modulus and deformation was better in carbon fibre reinforced laminates than glass fibre reinforced laminates in terms of
Medupin et al. (2019)	Comparative Study of Multi-walled Carbon Nanotube Reinforced Natural Rubber Nanocomposite and Multiflex Dynamic Response – 2 Artificial Foot	In this study, the functional properties of self-assembling nanocomposites were compared with those of M.DR2 prostheses. The problem of homogeneity of multilayer carbon nanotubes (MWCNTs) in host matrices was resolved by the addition of Sodium Dodecyl Benzene sulfonate (NaO3S) C18H29	The carbon nanotube (CNT) was created using CCVD (catalytic chemical vapour deposition), and the carbon nanowires (NCs) were manufactured using an electrically hot hydraulic press	The wear rates of DR2 vs. DR2–3 are also better. According to the Wearing Rate results, DR2 Wears about 32% faster than DR2–3 Wearing rate. Therefore, if you have a foot prosthesis with an anthropomorphic design, you should go with domestic material instead of foreign equivalent

In Table 3, feet in K1, designed for people who engage in activities of daily living that involve light and stable walking with a walking aid (moving around the home, moderate walking in the community) that do not require high energy storage and recovery For people overcoming basic environmental obstacles (cliff, stairs) (K2), manufacturers

mostly offer fibreglass or carbon/fibreglass products. Carbon fibres with the highest energy performance material are used for K3 and K4 users. Regarding the modifications of the composite materials used in leg prostheses (forms, fibre mass, bending), information about them is, as a rule, a commercial secret of the companies concerned and proves the unique value of the product. The main characteristics of foot are a high strength/density ratio, shock absorption and the ability to fall smoothly. The type of fibre, the number of layers, the method of installation and the method of connecting the substrates determine the efficiency of the leg. The higher the K level, the stiffer the leg should be, the tighter the braid and the higher the density. A review of the energy storage leg market shows that glass fibre or carbon glass fibre is used for the average active patient (K2), while carbon fibre combined with epoxy resin is the most common active material due to its lightest and most durable properties and very active patients (K3, K4). There is little information in the literature about the exact modifications of the compounds (type of braid, bulk content of certain fibres), because it is a closely guarded knowledge of the companies. The elastomeric properties of prosthetic foot materials are critical in determining product life. Prosthetic foot elastomer properties. In this study, three prosthetic foot types were used: Imported A, Imported B, Local C, Hardness, Tensile strength, Erosion, Tear strength, Compression. Local C and Imported B Harder than Imported A. Best for Tensile Stresses and Erosion at Break of Local C Best. For Tear Strength Lowest Score in Compression Testing Good for Preventing Permanent Deformation. Bakhtawar Sehar investigated the mechanical strengthening of carbon fibre composites for the production of legs. He concluded that as the number of carbon fibre layers increased, the tensile strength of carbon fibre laminates in successive samples generally improved. The tensile strength of PMMA/SR polymer blends increases when improvement of the tensile strength of the polymer blends with the reinforcement of the prosthetic foot material with carbon fibre. When the reinforced polymer is mixed with random fibres, the load is concentrated at the ends of the short fibres and the orientation of the fibres is randomly distributed in the matrix, allowing the load to be transferred from the matrix to the fibres across the interface region. When used as a reinforcing material, CF has a weak and high tensile strength, which increases the tensile strength of polymer blends, so the tensile strength and elastic moduli increased as the reinforcement content increased. Effect of CF on elongation of PMMA, elongation increases with increasing rubber content and decreases with increasing CF because as the rubber content increases in polymer blends, the polymer chains relax. Movement, the polymer chain causes a decrease in elongation (Hadi and Oleiwi, 2015). The reinforcing material added to the prosthesis and the polymer mixture increases the bending strength, the bending factor and has improved to be the best reference material for the leg (Hadi and Oleiwi, 2015).

Hassan Saad Mohammed carried out a study on the development of new composite materials for the foot prosthesis industry. The elongation and impact energy at break decreased significantly, but the yield and the tension at break improved by approximately 2–3 times compared to HDPE. The elongation is increased by 27% at break compared to HDPE values. The final yield strength and the ultimate impact strength are decreased when 10% linear low density polyethylene (LLDPE) is mixed with 90% HDPE (Almuslehi, 2014). The mechanical properties of hybrid and polymer matrix composites increased significantly for the manufacture of the part foot prosthesis. The Fatigue life of both Perlon Carbon-Perlon Fibreglass and Hybrid Carbon Glass Fibres is increased (Hussain, 2017). Generally, increasing the number of carbon fibre layers increases the

tensile strength of the laminates, thus increasing the mechanical strength of the carbon fibre composites used for the prosthetic foot. The highest tensile strength of this test protocol is reported for a carbon fibre sample made with 10 layers of carbon fibre. The strain rate increases when the loading rate is increased from 2 mm/min to 5 mm/min when the fabricated samples are subjected to the tensile test. The composite foot is designed and modelled by Hasan Saad Mohammed and is used in the rehabilitation of the lower limb amputee. The new weight of the composite prosthesis is about 2% lighter than the previous one. The new foot has better life cycle properties covering the leg life cycle of 7.5° (1049.135) and 896.213 (Mohammed, 2020). The foot has the most load-bearing capacity, and sample 3, with compressive strength 8.79% when loaded with breaking force 330 N, has a modulus (622.53%). Step analysis shows final swing & heel strike at selected height (8 cm) and tension (0%). Early and mid-stance (0.3%) and height (7.7%) are tension and height respectively. Mechanical properties of Carbon Matrix Composites of Blade Running Proxies. The best composite of fibre and orthocrylic resin is the one with the highest mean tensile strength of 483.94%. For Runner blade, Combination of Carbon Fibre and Epoxy Matrix can be used for the artificial foot as it has higher energy absorption under the impact loads. The results of this study can be used as a guide for future work on prosthetic materials.

Table 3 Energy storing feet

<i>Types of legs</i>	<i>k-level</i>	<i>Efficiency [%]</i>	<i>Product offering material</i>	
Energy storage	K2	30–50	Equilibrium	Carbon/glass fibre
			Terion 1C1	Glass fibre
			BK- Bundle	Glass fibre
	K3	45–60	Roadflexion	Carbon fibre
			TLM Food	Carbon fibre
			Re-Flex Shock	Carbon fibre
	K4	55–70	Roadwalking	Carbon fibre
			Triton 1C61	Carbon fibre
			Vari-Flex	Carbon fibre

In Athlete's Foot Effect Of Kevlar Fibre Reinforcement with Carbon Fibre and Glass Fibre on Performance Carbon Fibre Reinforced Laminates Have Higher Young's Modulus and Deformation (Talla, 2022). Comparison of natural fibre-based composite foot and carbon fibre prosthesis for use in poor countries was that the proportion of natural fibre foot prostheses was significant stiffer compared to a carbon fibre foot.

5 An overview of the clinical use of foot prostheses

In Table 4, when compared to the carbon fibre and bionic foot effects on ground walking and treadmill walking in Transtibial Amputees, the ECW for floor and treadmill walking with Proprio-Foot® was the last floor walking test (Delussu, 2013). We compared the

mechanical and dynamic characterisation of leg prostheses during weighted and unweights walking in active users. Ankle-foot prosthetic systems with matching foot wedge structures are better suited for weight-bearing walking. Lee Childers did one study on how increasing the energy return of a prosthetic leg affects total body mechanics when walking on flat ground and on slopes. Fibreglass legs had higher energy absorption during walking ($P = 0.01$) and no difference in energy recovery ($P = 0.37$). The results of this study show that the new fibreglass ESR leg performed better than the traditional design using carbon fibre material (Kaufman and Bernhardt, 2021). The drop analysis of the new model carbon fibre prosthetic leg was an inverted pendulum-like device that was built to achieve the required test and calculated the teardrop shape of the prosthesis. Manufacturing process.

Table 4 An overview of the clinical use of foot prostheses

Delussu (2013)	Assessment of the effects of carbon fibre and bionic foot during overground and treadmill walking in transtibial amputees	The ECW tests were carried out on a flat floor and on slopes at -5% , -0% and 12% on a treadmill	Tests were conducted at 6 data collection sites: 1) with a conventional suction system 2) with a 7-weeks Hypobaric Suspension System with DCF 3) 1 h after 1 day of Proprio Foot® use with HSS 4) 3 additional 30-day test sessions (i.e., 30, 60, 90 days of use with HSS)	The bionic foot made walking more energy efficient, especially when walking on the floor
Koehler-McNicholas et al. (2018)	Mechanical and dynamic characterisation of prosthetic feet for high activity users during weighted and unweighted walking	The mechanical properties of the ankle-foot prosthesis (i.e., foot stiffness) as well as dynamic performance (i.e., rocker radius and effective leg length ratio) as well as late stance energy return were analysed to determine whether ankle-foot prostheses are able to support weight-bearing walking	Foots are intended to be used by active users. Load-deflection curves for 9 ankle-foot prostheses were obtained using a servo hydraulic test frame with load cell. Effective fall form characteristics and energy recovery measures for late stance Quantitative gait analysis was performed on three unilateral Transtibial Amputees	Conformal foot wedges may help your ankle-foot system better adjust to weight bearing walking, lowering your metabolic rate during strenuous physical activity

Table 4 An overview of the clinical use of foot prostheses (continued)

Childers (2018)	Increasing prosthetic foot energy return affects whole-body mechanics during walking on level ground and slopes	Prosthetic foot energy recovery influenced walking mechanics on various slopes. Five patients with unilateral transtibial amputation completed a treadmill walk at 1.1 m per second in three conditions	The new foot demonstrated greater range of movement ($p = 0.0012$), and produced greater energy ($p < 0.0012$). The new leg exhibited greater range of movement and produced greater energy than the conventional foot	Prosthetic limb propulsion increased energy correlated with increased CoM energy change ($p = 0.012$) and prosthetic limb propelled decreased CoM energy
Halsne (2020)	The effect of prosthetic foot stiffness on foot-ankle biomechanics	The impact of the commercial prosthesis foot stiffness category on the biomechanics of the foot-ankle, on gait symmetry, on community mobility, and on perceived relative foot stiffness	Based on the data collected in the movement analysis laboratory, the fall form of the prosthetic leg during walking and the thrust and work of the ankle joint were determined	Seventeen men with a transtibial amputation completed the study. The drop radius of the foot increased with increasing stiffness classes of the foot
Wurdeman (2017)	Step Activity and 6-Minute Walk Test Outcomes When Wearing Low-Activity or High-Activity Prosthetic Feet	Determine changes in ADSC (average daily step count) and 6MWT (6min walk test) in LA foot and ESAR foot	A 6-week, randomised crossover study was conducted in patients ($n = 28$) who had suffered a transtibial amputation	In the 6MWT, there was a similar difference between LA and ESAR ($P = 0.871$), and ADSC ($p = 0.076$)
Delussu (2013)	Assessment of the effects of carbon fibre and bionic foot during overground and treadmill walking in transtibial amputees	Step energy (proprio-foot1) was measured while walking on the floor and running on the treadmill (different inclines)	Treatment-Assisted Testing (TTAs) were also included. Electrochemical Work (ECW) tests were conducted on a standard floor and on a treadmill at 5%, 0% and 12% inclines	

Table 4 An overview of the clinical use of foot prostheses (continued)

Kaufman and Bernhardt (2021)	Functional performance differences between carbon fibre and fibreglass prosthetic feet	The biomechanical performance of the prosthetic leg as well as the prosthetic quality-of-life was evaluated using fibreglass prostheses paired with conventional carbon fibre EQS models	Gait data showed an increase in ankle dorsal flexion (andlt; $p = 0.01$), similar durations of ankle moments ($p = 0.07$), and an increase in ankle strength ($P = 0.01$) for the fibreglass leg	When walking, the fibreglass leg absorbed more energy than the non-fibreglass leg ($P = 0.01$), but the energy return was the same (0.37)
Hamzah and AbdulhessenGatta (2019)	Roll-over analysis of a new design carbon fibre prosthetic foot	Many researchers have adopted a quasi-static drop test to calculate the droplet shape of the prototype legs	Rotational properties were evaluated as follows: effective bend radius of approximately 202 mm, bend centre of 26.55 mm, and forward motion relative to stem angle were plotted	
Koehler-McNicholas et al. (2018)	Mechanical and dynamic characterisation of prosthetic feet for high activity users during weighted and unweighted walking	adapt to weight-neutral walking by assessing mechanical properties (i.e., foot rigidity and dynamic performance)	Stiffness in feet varied with teardrop radius, and true foot length ratios were low relative to weighted walking. In addition, feet with more flexible plantar wedge structures showed a later stance energy recovery compared to feet with more rigid plantar wedge structures	Achilles' heel prosthetic systems with contoured foot wedges may be better adapted to weight bearing walking, lowering the metabolic costs of strenuous physical activity.
Yang (2018)	Differences in gait patterns in unilateral transtibial amputees wearing two energy-storing leg prostheses, 10 unilateral transtibial amputees. Two dynamic response legs of different shapes, either 1C30 Trias or 1C60 Triton, were used for each subject	Step analysis was used to obtain spatiotemporal and kinematic as well as kinetic data. A parallel comparison showed an asymmetry in frequency in 1C30 Traces	The ratio of position to rotation and ankle durations through mid-position were similar between the 1C60 and 1C30 Tritons. Spatial, kinematic, and kinetic data did not indicate a statistically significant difference between the prostheses	The difference between 1C60 and 1C30 was the difference in stance and swing ratio, as well as the difference in ankle dorsal flexion through the middle of the body compared to 1C30

CAD modelled ankle support Monoblock EVA simplified the manufacturing process. Reduced foot weight Improved wearer's gait profile Improved flat foot profile, Mechanical and dynamic characterisation (Hamzah and AbdulhessenGatta, 2019). Active users' prosthetic feet during weighted and no weighted walking Ankle-foot prosthesis systems with corresponding foot wedge structures are better able to adjust to weighted walking Reduced metabolic cost for physically demanding activities Symmetrical gait (Koehler-McNicholas et al., 2018) Gait patterns (Yang, 2018). For each object, two dynamic response legs (1C30 and 1C60) of different shapes (1C60 and 1C30) were used. Energy-Storing leg implants (1C60) Gait pattern (Yang, 2018).

6 Result analysis

Dynamic response prosthetic feet are innovative devices designed to mimic the biomechanical characteristics and functions of a natural foot during walking and running. These advanced prosthetic feet utilise various technologies and materials to provide improved energy storage and return, stability, and a more natural gait for amputees. Here is an overview of the design, technology and applications of dynamic response prosthetic legs in amputation rehabilitation: Here are some key features and considerations in the design of dynamic response feet:

Energy return: Dynamic response feet are engineered to store and release energy during walking or running. It can absorb the impact force generated when the foot hits the ground and then release the stored energy during the push phase to propel the user forward.

Flexibility: The design of the foot incorporates flexibility to allow it to adapt to different surfaces and terrain changes. This flexibility helps maintain stability and balance when walking.

Ankle movement simulation: Some dynamic response feet include mechanisms that mimic natural ankle movement, providing a smoother, more realistic walking experience. This feature is especially important for amputees who lead more active lifestyles or play sports.

Weight and materials: Materials used in the foot structure must be lightweight yet strong to ensure comfort and durability. The weight of the prosthesis can significantly affect the wearer's gait and overall comfort.

Alignment: Proper alignment of the dynamic response foot and the amputee's residual limb is critical to achieving optimal gait patterns. This requires precise adjustments and fitting by a qualified prosthetist.

Customisation for the user: Each amputee's needs and behaviours are unique. A good dynamic foot design should provide a customised fit that suits your individual needs and lifestyle.

Safety and stability: Designs should focus on safety and stability, minimising the risk of falls and injuries during everyday activities. Durability and Maintenance: Prosthetic limbs are subject to regular wear and tear. Dynamic Response feet should be designed to withstand the rigors of everyday use and be easy to maintain.

FDA approval and certification: All prosthetic foot designs must meet relevant regulatory requirements to ensure safety and effectiveness. It is important to remember that prosthetic technology is constantly evolving, and new advancements are constantly being made to improve the function and comfort of dynamically responsive feet. Individuals interested in using these prosthetics should consult with a qualified prosthetist to determine the most appropriate option based on their specific needs. Technology for dynamic response prosthetic foot systems. Dynamic response prosthetic foot systems have made significant advances in technology. They are designed to mimic the natural movements of the human foot, providing amputees with more comfortable and efficient walking. The main technologies used in dynamic response prosthetic foot systems are:

Carbon fibre composites: Carbon fibre is a lightweight, durable material commonly used in dynamic prosthetics. It provides flexibility and responsiveness, allowing the foot to adapt to different surfaces and providing energy return when walking or running.

Ankle and toe springs: Dynamic prosthetics often include mechanical components such as ankle and toe springs. These springs store and release energy during the gait cycle, mimicking the movement and function of natural muscles and tendons.

Hydraulic damping: Some advanced prosthetics use hydraulic damping to control the speed of movement and absorb shock while walking or running. This feature increases user stability and comfort.

Sensors and microprocessors: Modern dynamic prosthetics may include sensors and microprocessors that monitor movement and adjust foot responses in real time. These sensors can detect changes in terrain and user activity and adjust foot movements accordingly.

Bluetooth connectivity: Bluetooth technology can be integrated into dynamic prosthetics to provide wireless communication with smartphones or other devices. This connection allows the user to access data and control specific functions of the prosthetic limb via a mobile application.

Machine learning and AI: Artificial intelligence (AI) and machine learning algorithms can be used to improve the adaptability and responsiveness of dynamic prosthetics. By learning the user's movement patterns and adjusting the foot motion accordingly, the foot can become more personalised and efficient over time. **Waterproof and Dustproof Design:** Many dynamic foot prosthetics are designed to be waterproof and dustproof, allowing the user to engage in a variety of activities without worrying about damaging the internal components.

It is important to note that technology continues to evolve rapidly, and new advancements may have been made since my last update. Therefore, it's always a good idea to consult with a prosthetist or a healthcare professional specialising in prosthetics for the most up-to-date information and to find the best solution tailored to an individual's specific needs.

Dynamic Response Prosthetic Foot Mechanism Study The study of dynamic response prosthetic foot mechanism is an important research area in the field of prosthetics and orthotics. Prosthetic feet play an important role in enabling disabled people to walk, run

and participate in various activities by simulating the function of the biological foot. The purpose of this foot system is to provide the user with more mobility, stability and functional strength. Key aspects and considerations in the study of dynamic response prosthetic foot mechanisms include:

Biomechanics: Understanding the biomechanics of the human foot during various activities is critical to designing prosthetic feet that closely mimic movement. Researchers analyse gait patterns, coordination, ground response, and energy changes during walking, running, and other activities to inform the design process is Equipment and construction. This allows the foot to absorb impact when the user lands and rebound to store energy during push-off, resulting in better results. Materials used to design dynamic response in prosthetic feet. These products are selected and designed to provide the necessary levels of flexibility, stability, and performance. Foot Researchers are taking user feedback and experiences into account to improve the design and performance of prosthetic foot systems.

Health benefits and quality of life: Studies are examining how prosthetic foot performance affects overall health, comfort, and well-being for frail people. Measures' walking performance, fatigue reduction, joint health, and impacts the user's musculoskeletal system. Advantages and limitations. These comparative studies help determine which prosthetic foot mechanism is best for user groups and activities. Researchers are investigating the integration of smart devices, sensors, and control algorithms to improve the performance and adaptability of these artificial devices. Increase mobility and comfort for an active and fulfilling life. Continued research in this area will lead to the development of artificial joints that will improve the function of the natural foot.

7 Conclusion

The technical and clinical application of dynamic response feet for both transfemoral and transtibial amputees has never been thoroughly examined before, until now, with this systematic review. 43 papers were reviewed in this systematic review. The findings show that over the past 20 years, several dynamic response foot designs have been synthesised worldwide; however, there has been uncertainty regarding prescription criteria, design parameters, and the kinematic performance of these designs and their equivalents. There are many different geometries for dynamic response feet, but there aren't many techniques for comparing how well they work. Nowadays, computer-aided engineering helps to select and design dynamic response feet that are better in terms of quality, performance, and safety. Utilising the components of a prosthetic foot, gait analysis of trans-femoral amputation offers a reliable method for correlating the experimental findings. A novel tuning system that can alter the control parameters governing prosthesis dynamics during a bipedal gait cycle is made possible by machine learning techniques and control algorithms. To develop and implement standardised measures on prosthetic feet that are effective in terms of their use, function, durability, and cost-effectiveness, more research is required.

References

- Abdulradi, R.S., Hamzah, M.N. and Andul-Sahib, I.A-H. (2024) 'A review of the materials' characteristics and prosthetic foot models', *J, Electrical Systems*, Vol. 20-9s, pp.877–883.
- Almuslehi, H.S.M. (2014) 'Develops new composite materials for prosthetic foot industry', *International Journal of Materials, Methods and Technologies*, Vol. 2, No. 4, August, pp.1–14, ISSN: 2327-0322.
- Al-Zubaidi, D.H.J. and Al-Shammari, M.A. (2022) 'Theoretical analysis of a new design of dynamic prosthetic foot', *International Journal of Mechanical Engineering*, Vol. 7, No. 1, January, ISSN: 0974-5823, pp.4667–4680.
- Bates, T.J., Fergason, J.R. and Pierrie, S.N. (2020) 'Technological advances in prosthesis design and rehabilitation following upper extremity limb loss', *Curr Rev Musculoskelet Med.*, Vol. 13, No. 4, August, pp.485–493, DOI: 10.1007/s12178-020-09656-6, PMID: 32488625, PMCID: PMC7340716.
- Childers, W.L. (2018) 'Increasing prosthetic foot energy return affects whole-body mechanics during walking on level ground and slopes', *Sci Rep*, Vol. 8, No. 1, 29 March, p.5354.
- Delussu, A.S. (2013) 'Assessment of the effects of carbon fiber and bionic foot during overground and treadmill walking in transtibial amputees', *Gait and Posture*, Vol. 38, No. 4, September, pp.876–882.
- Hadi, A.N. and Oleiwi, J.K. (2015) 'Improving tensile strength of polymer blends as prosthetic foot material reinforcement by carbon fiber', *J. Material Sci Eng.*, Vol. 4, p.158.
- Halsne, E.G. (2020) 'The effect of prosthetic foot stiffness on foot-ankle biomechanics and relative foot stiffness perception in people with transtibial amputation', *Clinical Biomechanics*, Vol. 80, December, p.105141.
- Hamzah, M. and AbdulhessenGatta, A. (2019) 'Roll-over analysis of a new design carbon fiber prosthetic foot', *University of Thi-Qar Journal for Engineering Sciences*, Vol. 10, No. 1, pp.36–42.
- Hussain, H.S. (2017) 'Mechanical properties of hybrid and polymer matrix composites that used to manufacture partial foot prosthetic', *Al-Nahrain Journal for Engineering Sciences (NJES)*, Vol. 20, No. 4, pp.887–893.
- Ismail, R., Paras Utami, D., Arid Irfai, M., Jamari, J. and Bayuseno, A.P. (2021) 'Mechanical properties of carbon-matrix composites for a blade runner's artificial leg', *Cogent Engineering*, Vol. 8, No. 1, Article No. 1923382, pp.1–12.
- Johnson, W.B., Prost, V., Mukul, P. and Winter, V.A.G. (2023) 'Design and evaluation of a high-performance', *Low-Cost Prosthetic Foot for Developing Countries. Journal of Medical Devices*, Vol. 17, No. 1, p.011003.
- Kadhim Oleiwi, J. and Namah Hadi, A. (2016) 'Design of prosthetic foot from polymer materials reinforced by carbon Fibers', *Engineering and Technology Journal*, Vol. 34, No. 9A, pp.1744–1754.
- Kadhim, F.M. (2022) 'Optimal material selection for manufacturing prosthetic foot', *Science and Technology*, 21 July.
- Kaufman, K.R. and Bernhardt, K. (2021) 'Functional performance differences between carbon fiber and fiberglass prosthetic feet', *Prosthetics and Orthotics International*, Vol. 45, No. 3, June, pp.205–213.
- Kelechi, K.D., Ndubuka, G.I., Onwukamuche, K.C., Ofoegbu, M.C., Elueke, U.C., Igwe, A.C. and Ekezie, J. (2020) 'Biomechanical properties of rattan cane in the design and', *Fabrication of Prosthetic Foot. Asian Journal of Applied Sciences*, Vol. 8, No. 6, pp.308–324.
- Khafidh, M., Marwa, P.A., Alfajr, B., Suryawan, D., Kistriyani, L. and Ismail, R. (2023) 'The mechanical properties of elastomeric materials in prosthetic feet: Comparison between local and imported products', *AIP Conference Proceedings*, AIP Publishing, Vol. 2568, No. 1, March.

- Koehler-McNicholas, S.R., Nickel, E.A., Barrons, K., Blaharski, K.E., Dellamano, C.A., Ray, S.F. and Hansen, A.H. (2018) 'Mechanical and dynamic characterization of prosthetic feet for high activity users during weighted and unweighted walking', *PloS one*, Vol. 13, No. 9, p.e0202884.
- Li, B., Xu, G., Teng, Z., Luo, D., Pei, J., Chen, R. and Zhang, S. (2024) 'Intelligent ankle-foot prosthesis based on human structure and motion bionics', *J. Neuroeng Rehabil.*, Vol. 21, No. 1, 13 July, p.119, DOI: 10.1186/s12984-024-01414-w, PMID: 39003459; PMCID: PMC11245770.
- Manual on Disability Statistics (2012) Govt of India, Ministry of Statistics and Programme Implementation, CSOMSS2012.
- Mathur, M.K. (2012) 'Prosthetic fittings limitations and its present scenario in India and abroad', *Indian Journal of Physical Medicine and Rehabilitation*, Vol. 23, No. 2, pp.82–88.
- Medupin, R.O., Abubakre, O.K., Abdulkareem, A.S., Muriana, R.A., Abdulrahman, A.S. and James, J.A. (2019) 'Comparative study of multi-walled carbon nanotube reinforced natural rubber nanocomposite and multiflex dynamic response – 2 artificial foot', *Journal of Physics: Conference Series*, IOP Publishing, Vol. 1378, No. 2, December, p.022054.
- Mohammed, H.S. (2020) 'Design and modeling the prosthetic foot from suitable composite materials', *American Journal of Engineering and Applied Sciences*, Vol. 13, No. 3, pp.516–522.
- Nayak, S.S., Mohapatra, A.K., Maharana, S., Mishra, B., Pattanaik, B.K.S.S. and Paikaray, B.K. (2024) 'Computational analysis of gait patterns in transfemoral amputees: polycentric and weight-activated knee joints', *International Journal of Computational Biology and Drug Design*, Vol. 16, No. 2, pp.147–166.
- Omasta, M. (2012) 'Finite element analysis for the evaluation of the structural behaviour, of a prosthesis for trans-tibial amputees', *Med Eng Phys*, Vol. 34, No. 1, January, pp.38–45.
- Sam, M., Hansen, A.H. and Childress, D.S. (2004) 'Characterisation of prosthetic feet used in low-income countries', *Prosthet Orthot Int.*, Vol. 28, No. 2, August, pp.132–140.
- Sehar, B. (2022) 'The impact of laminations on the mechanical strength of carbon-fiber composites for prosthetic foot fabrication', *Crystals*, Vol. 12, p.1429.
- Tacca, J.R., Colvin, Z.A. and Grabowski, A.M. (2024) 'Greater than recommended stiffness and power setting of a stance-phase powered leg prosthesis can improve step-to-step transition work and effective foot length ratio during walking in people with transtibial amputation', *Front Bioeng Biotechnol.*, Vol. 12, 1 July, p.1336520, DOI: 10.3389/fbioe.2024.1336520, PMID: 39011154; PMCID: PMC11246994.
- Talla, H.K. (2022) 'Study the effect of reinforcing Kevlar fibers with carbon fibers and glass fibers on the performance of the athletic prosthetic foot', *Basrah Journal for Engineering Sciences*, Vol. 22, No. 2, pp.41–48.
- Talla, H.K., Oleiwi, J.K. and Hassan, A.K.F. (2021) 'Performance of athletic prosthetic feet made of various composite materials with PMMA matrix: numerical and theoretical study', *Journal of Composite & Advanced Materials/Revue des Composites et des Matériaux Avancés*, Vol. 31, No. 4, p.257.
- Tarrade, T., Dakhil, N., Behr, M., Salin, D. and Llari, M. (2021) 'Real-time analysis of the dynamic foot function: a machine learning and finite element approach', *Journal of Biomechanical Engineering*, Vol. 143, No. 4, p.041005.
- Walke, K.M. and Pandure, P.S. (2017) 'Mechanical properties of materials used for prosthetic foot: a review', *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*, Vol. 61, No. 65, pp.61–65.
- Wurdeman, S.R. (2017) 'Step activity and 6-minute walk test outcomes when wearing low-activity or high-activity prosthetic feet', *Am J Phys Med Rehabil.*, Vol. 96, pp.294–300.
- Yang, J.R. (2018) 'Differences in gait patterns of unilateral transtibial amputees with two types of energy storing prosthetic feet', *Ann Rehabil Med.*, Vol. 42, No. 4, August, pp.609–616.