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Review Article

Adaptive Foot in Lower-Limb Prostheses

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The human foot consists of complex sets of joints. The adaptive nature of the human foot enables it to be stable on any uneven surface. It is important to have such adaptive capabilities in the artificial prosthesis to achieve most of the essential movements for lower-limb amputees. However, many existing lower-limb prostheses lack the adaptive nature. This paper reviews lower-limb adaptive foot prostheses. In order to understand the design concepts of adaptive foot prostheses, the biomechanics of human foot have been explained. Additionally, the requirements and design challenges are investigated and presented. In this review, adaptive foot prostheses are classified according to actuation method. Furthermore, merits and demerits of present-day adaptive foot prostheses are presented based on the hardware construction. The hardware configurations of recent adaptive foot prostheses are analyzed and compared. At the end, potential future developments are highlighted.

1. Introduction

Lower-limb assistive devices can be divided into two main categories as orthosis and prosthesis. The orthosis is an orthopaedic apparatus which is used as support for adjusting deformities to improve functionalities of moving body parts whereas prosthesis is an artificial replacement for a missing body part [1, 2]. According to the literature survey on amputation in 2005, the United States (USA) recorded about 1.6 million lower-limb amputees. It was predicted that the number of lower-limb amputees would be increased to 3.6 million over the span of the next 50 years [3]. Another Tanzania-based survey reported 86.4% of total amputees as lower-limb amputees [4]. A survey conducted in Brazil reports that 25% of total amputees require foot prostheses solutions [5]. Long-term passive flat foot prostheses users tend to suffer from physical injuries such as osteoarthritis, osteopenia, and subsequent osteoporosis due to musculoskeletal imbalances or pathologies [6, 7]. Foot prosthesis with flexible adaption capabilities is a precaution for the above-mentioned injuries [6, 7]. Statistical data and possible physical injuries reflect the necessity of suitable and reliable adaptive foot prostheses which could mimic the human foot functionalities in commercial level. Foot amputees' lives can be uplifted and made comfortable and more productive to the society by developing advanced, reliable prosthetic solutions. Currently, some passive [8–16], active [17–19], and hybrid [20–30] adaptive foot prostheses have been developed with a focus on different functional requirements and design mechanisms.

The human foot has the adaptive capability which enables the foot to withstand any uneven surface. Necessary kinematic and kinetic adjustments are done to the gait pattern during ambulation by pedestrians in order to maintain stability on slopped or uneven terrains [31]. Normally, the human walking decisions are taken upon on human vision sensors and neural sensors. Amputees lack certain neural sensors due to the loss of their body part. The inability of surface adaption of the foot has significantly increased the load on the residual limb. Additionally, pressure ulcers and deep tissue injuries can occur as a result of significant pressure on a residual limb [32]. Lack of stability causes prostheses users to fall when entering an uneven surface [33]. Lack of inversion-eversion in ankle prosthesis can cause instability due to partial contraction with the surface. Suitable solutions for these physical and practical problems have to be addressed when designing an adaptive foot prostheses. However, most of the existing lower-limb ankle prostheses have not focused on developing a proper adaptive foot prosthesis for their ankle prosthetic devices. Instead, the passive flat prosthetic foot has been commonly used as the end connector for commercial lower-limb prostheses such as Otto Bock. Since passive flat foot prostheses have limited functional capabilities and other physical side effects as mentioned above, adaptive foot prostheses are essential to be developed to regain natural foot motions in lower-limb prostheses [34–37].

In this paper, authors have reviewed designs and developments of adaptive foot prostheses that have been proposed for lower-limb prostheses since 1997. It is essential to study design features, merits, and demerits of existing designs in order to enhance the field of adaptive foot prostheses. Some of the available reviews are focused on lower-limb prostheses [38, 39], control methods of lower-limb prostheses [40, 41], and prosthetic feet devices [42]. Versluys et al. [42] classified conventional feet, energy storing feet, and bionic feet upon control, comfort, and cosmetics. They have reviewed only a limited number of existing bionic foot devices and also adaptive mechanisms have not been considered for the review article. Since 2009, a lot of active foot prostheses have been introduced with novel mechanisms. In-depth review on adaptive foot prostheses is rarely found with those novel mechanisms. A prompt review paper on adaptive foot prostheses is very useful, not only to identify the current status of research but also to provide information to anyone in the field of developing adaptive foot prostheses. This paper is prepared based on existing adaptive foot prostheses. Some passive prostheses are available with notable design functionalities and mechanisms. They can be transferred into active designs with suitable design changes which lead to adding those devices into this paper. The focus of this paper remains in existing designs, their favourable and adverse design issues, and common solutions available in adaptive foot prostheses.

The systematic review on recent developments in foot prostheses has been done based on sets of design criteria. The papers were chosen based on preselected search keywords. Out of many scientific databases, the following were selected due to the availability of a higher number of the relevant manuscripts: IEEE Xplore, Elsevier, SAGE, InTech, PLOS ONE, ASME (American Society of Mechanical Engineer's Journal), and Journal of Rehabilitation Research & Development (JRRD). The paper selection was compiled upon PRISMA criteria [43]. The selected papers were initially screened, then the duplications were removed, and the papers were further refined due to irrelevance. Later search keywords were readjusted in order to obtain a higher number of relevant results. Finally, the search keywords "adaptive foot prostheses" were selected. The detailed review methodology is explained in Section 5 below.

The paper is structured as follows. In Section 2, the anatomy of the ankle and foot has been explained briefly in order to clarify the adaptive foot prostheses functional requirements. Section 3 presents requirements and design difficulties encountered in adaptive foot prostheses development. Classification of adaptive foot prostheses is presented in Section 4. The extended details, a method of literature selection for the analysis, and comparison and review of existing prostheses are included in Section 5. Finally, discussion and future directions are included in Section 6.

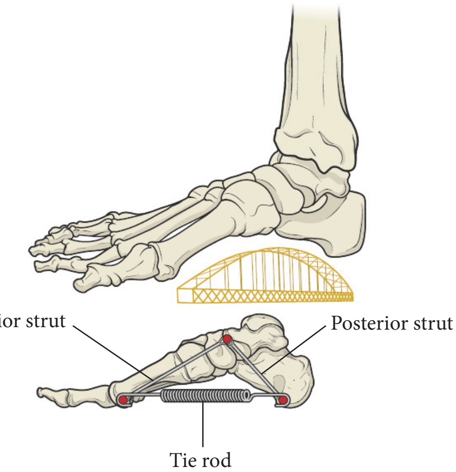


Figure 1: The arch of foot mechanism [45].

2. Anatomy of Ankle and Foot

The main function of the foot is performing gait cycle. Sufficient amount of mobility and stability is necessary for the foot to perform its tasks. Absorbing the ground reaction force is critically important for mobility. Stability is essential for well-balanced body posture [44]. The foot consists of 6 joints which can move along sagittal and transverse planes. Due to the complexity in foot joints, developing a foot prosthesis to mimic the human foot adaption capability is a challenging task. The anatomy of the human foot consists of 26 bones, 33 joints, 20 muscles, and over 100 ligaments [45, 46]. It can carry the human body weight due to its complex structure. The foot is capable of varying flexibility and elasticity of the complex structure to perform various challenging tasks such as running, climbing, balancing, jumping, hopping, and going up on the toes [45]. The foot bones are distributed along two main concurrent structures, known as the ache. There are three types which are medial longitudinal arch, lateral longitudinal arch, and transverse arch. The surface adaption (or flexibility and elasticity) of the foot occurs due to varying the arch angle of the foot (Figure 1). View along longitudinal (sagittal plane) arch is shown in Figure 2. The curvature of the bones of the foot provides a structure which is able to absorb high force repetitively similar to a bridge. Additionally, intrinsic and extrinsic muscles provide structural resilience by serving a tie rod as shown in Figures 1 and 2. As a result of contraction and relaxation of these muscles, the arch of the foot changes and increases the surface adaption capability of the foot. This geometric distribution combined with tendons and muscles creates foot windlass mechanism [47]. Windlass mechanism is used for moving heavy loads in engineering applications. Similarly, windlass mechanism provides the additional support for the foot arch to carry the load.

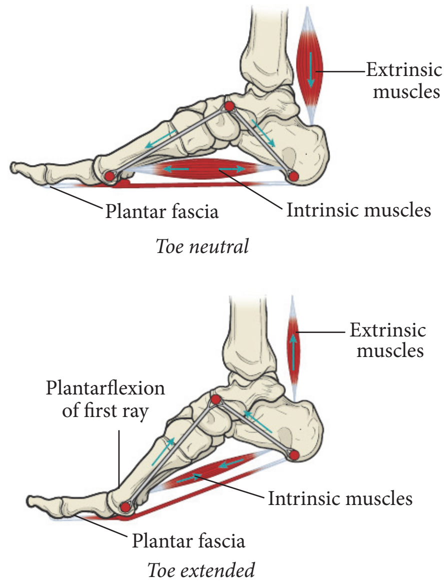


Figure 2: Windlass mechanism [45].

Table 1: Ranges of motions of human foot joints.

Motion	Human foot joint	Plane of movement	Range of motion
Dorsiflexion & plantarflexion	TC	Sagittal	N/A
	ST	Sagittal	−2.5° : 5°
Inversion & eversion	ST	Transverse	−10° : 20°
	MT - TN	Transverse	N/A
Abduction-adduction	ST	Frontal	−10° : 20°
Flexion & extension	MT-CC	Sagittal	N/A
	MTP (big toe)	Sagittal	(−) 80° : 40°
	MTP (toes 2–5)	Sagittal	(−) 60° : 40°
	Proximal IP (big toe)	Sagittal	0° : 90°
	Proximal IP (toes 2–5)	Sagittal	0° : 60°
	Distal IP	Sagittal	Hyper: 90°

The foot consists of three regions which are a hind foot (heel), midfoot, and forefoot (toe). The five major joints in the foot are ankle (or Talocrural (TC)) joint, Subtalar (ST) joint, Tarsometatarsal (TMT) joint, Metatarsophalangeal (MTP) joint, and Interphalangeal (IP) joint (Figure 3) [45, 46]. The hind foot consists of the calcaneus and talus. The midfoot consists of the navicular, cuboid, and the three cuneiforms. The forefoot consists of the metatarsals and phalanges. The ankle or TC joint is a hinge type joint which moves along the sagittal plane, providing the dorsiflexion and plantarflexion foot motions. The ST joint is a condyloid type joint which enables the movement along a transverse plane, providing inversion and eversion foot motions. The Midtarsal (MT) joint is in between ST joint and TMT joint which consists of two joints, namely, Talonavicular (TN) joint and Calcaneocuboid (CC) joint. The TN joint is a ball and socket type joint which enables the movement along transverse plane providing inversion and eversion foot motions. The CC joint is a modified saddle type joint which enables the movement along the sagittal plane, which provides flexion and extension foot motions. The TMT joint is a plane and synovial type joint which connects MTPs to the foot. The MTP joint is a condyloid type joint which moves along sagittal plane providing flexion/extension motions for proximal phalanges. This motion is essential when changing the arch of the foot on various surfaces. The IP joint is a hinge type joint which moves along sagittal plane which provides flexion/extension for middle and distal phalanges (Figure 3) [46].

There are rotation axes for each joint in the foot according to the plane of movement. The three cardinal planes of the human body are shown in Figure 4 which are a sagittal plane, transverse plane, and frontal plane. Some of the main rotation axes of the human foot are shown in Figure 5. Cardinal longitudinal axis of the foot is along the sagittal plane. Both ST joint and TC joint are joined to one another by talus bone, yet these two axes are more like perpendicular to one another due to the hinge and condyloid type joints. As a result, the toe can glide and roll. Knowledge of these movement planes and axes of rotation is important to understand the moving axes of existing foot prostheses. A better understanding of human foot anatomy is essential to identify design requirements. Table 1 summarized the ranges of motion of the above-mentioned human foot joints. (Consider supination as + direction and pronation as − direction). Distal IP has a small amount of extension which is known as hyperextension indicated in Table 1 as "hyper."

3. Requirements and Design Difficulties

The human foot consists of over 100 ligaments to control the five main joints. There are several design difficulties which can be incurred when developing an adaptive foot prosthesis. Complex nature of human foot anatomy makes it much difficult to mimic the adaptive nature of human foot through foot prostheses. The human foot maintains its stability by supinating/pronating along a longitudinal axis and plantar flexion/dorsiflexion along mediolateral axis. The surface contact area of the phalanges can be increased by flexing and extending them along mediolateral axis. A multi-DoF system with all the above-mentioned functionalities is a challenging task as actuators have to be arranged closer to each other while carrying the body load.

The human foot has arches along longitudinal and transverse axes which enable adapting to any surface by rotating along both directions. Developing a multidegrees of freedom system is a challenging task. The ankle joint is complex. Most of the existing prostheses have used high torque actuators for the ankle joint. Therefore sufficient space needs to be provided for ankle joint. Various mechanisms are available for transmitting the power to a prosthesis. Out of them, the most appropriate method has to be selected based on the power source, type of application, and expected weight of the prosthesis. The prosthesis should have the sufficient

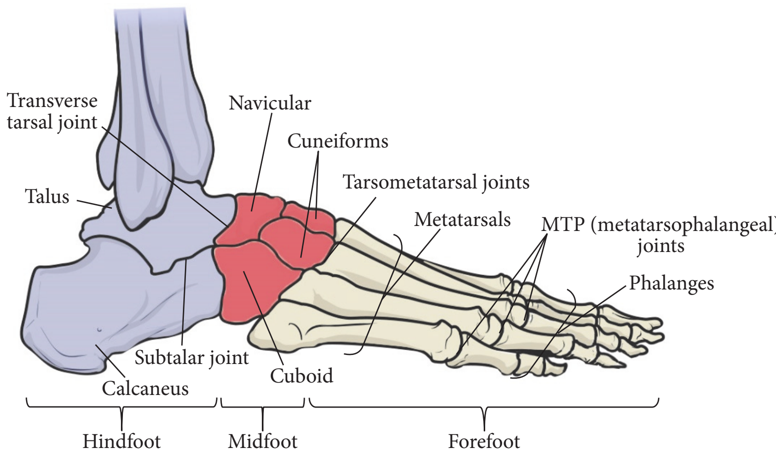


Figure 3: The human foot anatomy [45, 46].

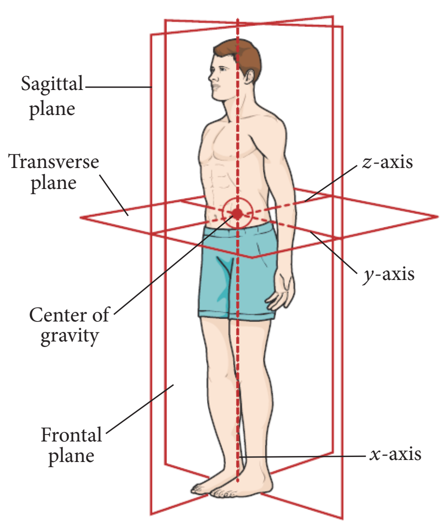


Figure 4: The three cardinal planes of the human body [45].

Table 2: Design requirements for a foot prosthesis development.

Requirement	Remarks
DOF	3DOF
Torque	Calculate by considering weight, type of mechanism, DOF, size, material (80–120 Nm)
Axis of rotation	Mediolateral axis, longitudinal axis, transverse axis
Type of mechanism	Coil spring, leaf spring, clutch, linkages, rolling joints, actuators, SEA, gears
Movable range	Refer to Table 1
Size	Approximately length 275 mm, width 100 mm, height 85 mm
Weight	Approximately 0.85–1.5 kg
Fabrication material	Carbon fiber or aluminum
Attachment method	Osseointegration, couplings, or pyramid adapters

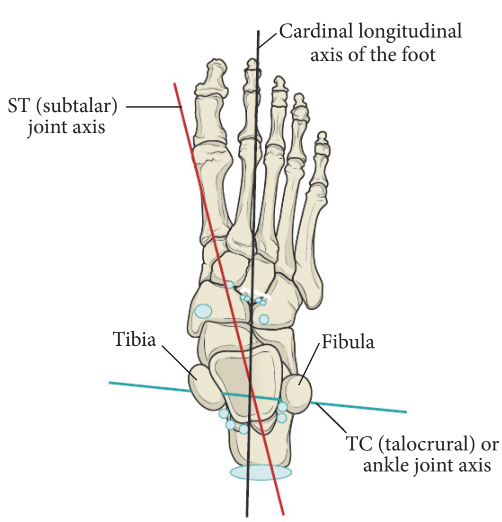


Figure 5: Human foot axes of rotation [45].

moving capability along each axis as given in Table 1. The dimensions of the device have to be within the limits of average human foot size. Adaptive foot prosthesis needs to be within average human foot weight. If it exceeds this, the amputee feels uncomfortable in long-term usage. High strength materials are needed for development as the foot needs to hold the total body load and large ground reaction forces for various activities of daily living (ADL) such as running, jumping, and hopping. Some developers have used lightweight, high strength polymer type materials instead of metals. The method of attaching the foot prosthesis to the remaining lower-limb or prosthesis device is another consideration that needs to be addressed. Table 2 provides a concise design requirements list.

4. Classification of Foot Prostheses

Prostheses can be classified according to the applications: upper limb prostheses, lower-limb prostheses, and other

Table 3: Methods of classification of adaptive foot prostheses.

Classification method	Parameters
Actuation method	Passive Active Hypird
DOF	Active DOF
Type of actuators	DC brushless motors DC servo motors AC servo motors
Power transmission method	Gear drives Chain drives Linkages Clutch drives
Energy regeneration methods	Series elastic actuators (SEA) Coil springs and clutch motors Linkages and camshafts Leaf springs
Attaching method	Coupling Pyramid adaptor

prostheses. Orthoses can be classified in two subcategories: exoskeletons and end effector connecting devices. There are different types of lower-limb prosthetic devices available based on an application which is for hip disarticulated amputees, above knee articulated amputees (transfemoral), knee articulated amputees, below the knee (transtibial), ankle disarticulated amputees, and partial foot amputees [1, 2]. Furthermore, adaptive foot prostheses can be classified into three categories which are a passive, active, and hybrid prosthesis. Passive prostheses are functionally lacking due to the mimicking of the human leg motions compared to the active prosthesis. Therefore the development of active prosthesis is essential. Yet they are still at the research level due to lack of design and control issues. Over the years a lot of transfemoral and transtibial prosthesis have been developed. However, there is a research gap in the field of development of an adaptive foot prosthesis. The hardware construction of adaptive foot prostheses can be classified into several categories which are classified upon actuation method, DoF, and types of actuators, based on power transmission method, energy regeneration method, and attaching method to the residual limb or transtibial prosthesis and so forth. Some of the classification methods are discussed below. Table 3 summarizes the classification of the hardware construction of adaptive foot prostheses devices.

(i) Actuation Method. Lower-limb adaptive foot prostheses are classified based on power source method. Passive prostheses are body-powered or use the power of user to actuate. Active prostheses are actuated using external power sources. Most of the present-day adaptive foot prostheses are combined with both passive and active joints. This method enhances the use of available energy during ambulation through passive joints and other required motions through active joints by external power sources.

(ii) DoF. Adaptive foot prostheses can be classified according to the number of active joints or externally power actuated joints like 1 DoF, 2 DoF, 3 DoF, and so forth.

(iii) Types of Actuators. There are various types of actuators that have been used in existing prostheses. They are DC motors, brushless DC (BLDC) motors, servo motors, and AC motors. Different types of DC motors are available such as brushless motors and servo motors.

(iv) Power Transmission Method. Prostheses transmit power using various methods such as gear drives, chain drives, and linkages mechanisms which are connected to actuators, clutch drives, and so forth. Additionally, belt drives, ball screw drives, and cable drive methods are possible.

(v) Energy Regeneration Method. Existing actuators have limited torque generation capability. Therefore some researchers have developed energy regenerative mechanisms to generate the required high torque. Series elastic actuator (SEA) is one of the most popular methods in modern days. Additionally, a combination of coil springs and clutch motors, linkages, camshafts with motors, and leaf springs with motors have been used in different existing devices.

(vi) Attaching Method. Attaching method of adaptive foot prostheses to the lower-limb prostheses is essential for the amputee's use. There can be two types of attaching ends which are connecting prosthesis to residual limb and attaching adaptive foot prosthesis to transtibial prosthesis of the transfemoral prosthesis. Ankle-foot couplings and pyramid adaptors are common among other attaching available methods. Additionally, socket attaching methods are possible.

5. Review on Adaptive Foot Prostheses

Foot prosthesis is used as the terminal device for the lower-limb prosthesis. There are passive and active adaptive foot prostheses. The passive prostheses are designed to be operated with user's body power and no actuator driven joints. Fully passive devices are relatively limited with motion capabilities. Active prostheses are designed to be controlled with externally powered actuator joints. It requires a well-designed control structure to control all the joints simultaneously to mimic the actual human foot movements. Active prostheses enhance the developers to focus more on the functionalities of the foot rather than mechanisms to power the device passively. The introduction of actuators to the active prostheses makes them much heavier compared to the passive prostheses. Due to the above-mentioned favourable and adverse drawbacks of passive and active prostheses, combined passive and active joints (or hybrid) prostheses have been developed by manufacturers lately. Hybrid prostheses have advantages over other prostheses which are improved workspace, higher functional capabilities, and larger range of motions.

The prosthesis gets bulky with the introduction of external power sources. As the prosthesis mass undergoes an increase, the user feels discomfort when using it over a

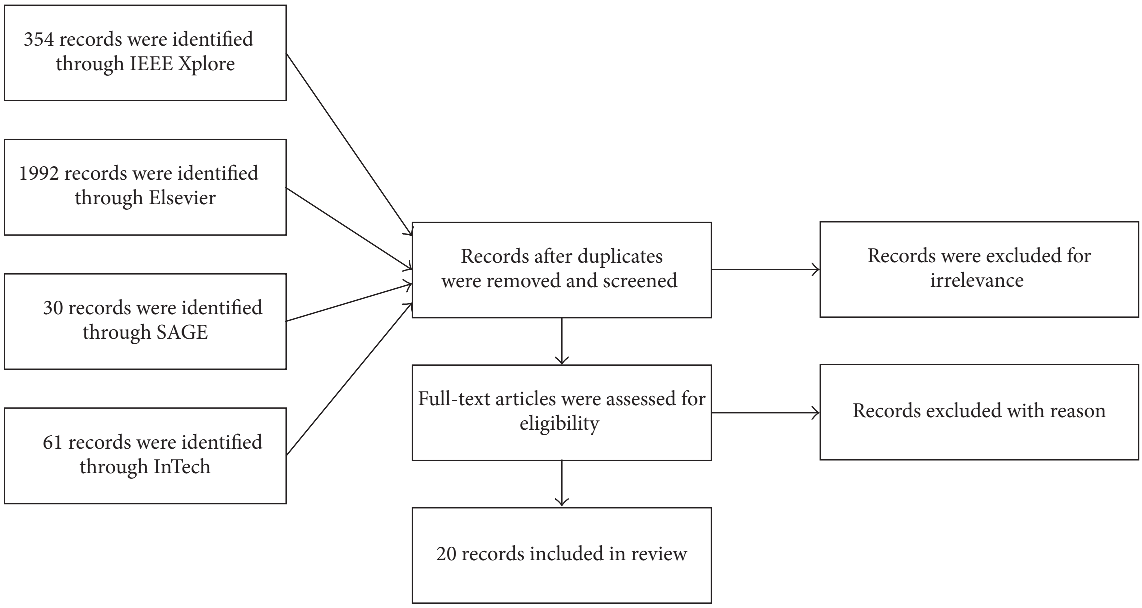


Figure 6: PRISMA flow diagram of the literature review process [43].

long period of time. Therefore energy saving mechanisms have been introduced by prosthesis developers to reduce the power requirement. The spring-based energy storing and regenerating methods like series elastic actuators (SEA) [48], parallel elastic actuators (PEA), clutchable series elastic actuators (CSEA) [49], continuously variable series elastic actuators [50], and so forth are some examples for such mechanisms. Attaching methods of adaptive foot prostheses to lower-limb prostheses are mainly coupling, pyramid type attachments. Aluminum is the commonly used material for the prototypes and expensive materials such as carbon fiber have been used in some of those developments. Tables 4, 5, and 6 provide a concise comparison of existing passive, active, and hybrid adaptive foot prostheses during 1997–2016. The weight of the adaptive foot prosthesis, actuation method and number of actuators, axis of rotation and equivalent human foot joint, working mechanism, moving range along each DoF, attaching method to remaining stump limb or transtibial prosthesis, and material used for the development are included.

In order to select databases for the paper, several generic keywords were searched such as "adaptive foot prosthesis, feet, ankle-foot prosthesis, lower-limb prosthesis, artificial limb, humanoid robots". IEEE Xplore, Elsevier, SAGE, InTech, PLUS ONE, ASME (American Society of Mechanical Engineer's Journal), and Journal of Rehabilitation Research & Development (JRRD) databases were chosen due to their high number of relevant search results. The search term of "adaptive foot prosthesis" was created in several iterations to obtain a larger number of relevant results. The search was limited to conference proceedings, journal papers, dissertations, and patents for the time period of 20 years from 1997 to 2017. Search results consisted of a significant number of control algorithms, medical researchers, and other robotic researchers. However, the basis was limited only to mechanical designs and developments. Most of those consisted of knee and ankle prostheses designs which had to be eliminated and only ankle-foot and foot were selected. With an in-depth study about available prostheses device designs and their focused area, most of them were refined and we retrieved the most appropriated few which were suitable for the topic of adaptive foot prostheses. Among the existing adaptive foot prostheses, flat foot designs were excluded. Only passive, active, and the combination of passive and active (i.e., hybrid prostheses) prostheses were adopted for the review. The number of search results obtained for each keyword in different academic databases is shown in Table 7.

The search retrieved a total of 2437 manuscripts from selected academic databases. The results were refined by manually screening for their relevance using the title and abstract. Selected remaining papers were studied further and we excluded the papers with no adaptive foot devices. A total of 20 papers were selected due to the high relevance to the topic of adaptive feet in prostheses. The PRISMA flow diagram in Figure 6 summarizes the review selection procedure. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) is a method used in systematic reviews in contemplation of improving the reporting quality [43]. Since most of the novel designs have been developed based on available patents and some patents are beyond the scope of this review, only 4 patents have been included in the review.

5.1. The Heel Foot [8]. The Heel Foot (Figure 8(a)) was developed by the University of Twente, Enscheda, Netherlands, in 2003. This is a single DoF passive plantar flexion adaptive foot prosthesis rotating along a mediolateral axis. Plantar spring controls the arch angle of the Heel Foot for maintaining stability. The potential energy stored in compressed plantar and heel springs starting from heel-off phase is used to push forward at the toe-off point. Four-bar linkage mechanism has been used for compression springs and varying arch angle. The Heel Foot was validated for relative joint angle, joint

Table 4: Comparison of passive-adaptive foot prostheses/foot designs in lower-limb prostheses.

Country	Name/year/reference number	Weight	Axis of rotation	Type of mechanism	Movable ranges	Attaching method	Material
Netherlands	The Heel Foot (2003) [8]	0.5 kg	Mediolateral axis MTP joint axis	Spring based	$(-)\ 20^{\circ} : 20^{\circ}$	Knee ankle coupling	Toe-carbon fiber, forefoot, heel—aluminum
Netherlands	fully passive transfemoral prosthesis (2011) [9]	1.05 kg	Mediolateral axis at MTP joint	Spring based and linkages	$0 : 30^{\circ}$ (toe)	Prosthesis ankle joint	Carbon fiber
United States of America (USA)	Prosthetic ankle-foot system (2014) [10]	1.04 kg	Mediolateral axis	Linkages and camshafts	$87^{\circ} : 105^{\circ}$	Pyramid adapter	Nylon 6/6, polyurethane rubber, maraging steel
Japan	Bipedal walking robot with oblique midfoot joint in foot (2015) [11]	N/A	Oblique axis at MTP joint	Truss and windlass mechanism	N/A	Nut and bolt	N/A
Italy	SoftFoot (2016) [12]	N/A	Parallel to mediolateral axis	Series of rolling joints	vary with the surface	Coupling	Rapid prototyping material
United States of America (USA)	Hindfoot and forefoot stiff foot prostheses (2017) [13]	N/A	Mediolateral axis	Flexible composite forefoot keel and hindfoot of varying stiffness	sagittal declination angle 15°	Pyramid adapter	Aluminum 7075-T6
United States of America (USA)	One-piece mechanically differentiated prosthetic foot (1997) [14]	N/A	Mediolateral axis	Flex due to polymeric material	N/A	Flange type nut and bolt connector	Light weight polymeric material
United States of America (USA)	Instrumented prosthetic foot (2012) [15]	N/A	Mediolateral axis	Flex due to polymeric material	N/A	Pyramid adapter	Durometer polyurethane
United States of America (USA)	Ankle-foot prosthesis of automatic adaptation (2014) [16]	N/A	Mediolateral axis	Spring and link based mechanism	$(-)\ 45^{\circ} : 80^{\circ}$	Pyramid adapter	Elastomeric Materials

Table 5: Comparison of active adaptive foot prostheses/foot designs in lower-limb prostheses.

Country	Name/year/reference number	Weight	Actuator	Axis of rotation	Type of mechanism	Movable ranges	Attaching method	Material
China	PANTOE 1 (2010) [17, 18]	1.47 kg	2 DC motors	Mediolateral axis at MTP joint	SEA	(−) 16° : 27°	Socket adaptor	Aluminum alloy
USA	Universal prosthesis emulator (2014) [19]	0.96 kg	1 DC motor	Mediolateral axis at MTP joint	Spring base	(−) 12° : 12°	Universal adaptor	7075-T651 aluminum

Table 6: Comparison of hybrid adaptive foot prostheses/foot designs in lower-limb prostheses.

Country	Name/year/reference number	Weight	Passive Joint	Actuator	Axis of rotation	Type of mechanism	Movable ranges	Attaching method	Material
Japan	Parallel four-bar linkage humanoid robot (2007) [20]	0.76 kg	Toe mechanism	1 DC servo motor	Mediolateral axis at MTP joint	Actuator based	0 : 44°	Humanoid ankle	Extra super duralumin
USA	Energy recycling foot (2010) [21, 22]	1.37 kg	Springs and clutches based mechanism	2 DC motors	Mediolateral axis at MTP joint	Coil Springs, clutch motor	N/A	Pyramid adapter	7075-T6 Aluminum, Stainless steel, Carbon/fiberglass
Japan	Adaptive bipedal deformable feet (2012) [23]	1.2 kg	Torsional Springs	2 Servo motors	Mediolateral axis at MTP joint	Torsional springs and servo motor combination	N/A	Nut and Bolt	Super soft urethane resin
Germany	An adaptive sensor foot for a bipedal and quadruped robot (2012) [24]	N/A	Bowden cables and dampers	2 BLDC motors	Mediolateral axis at MTP joint	Windlass mechanism	roll −20° to 10° pitch −30° to 20° yaw −10° to 10°	Coupling	Rapid prototyping material
Belgium	The AMP-foot 1.0 (2012) [25]	3 kg	Spring-based gear mechanism	N/A	Mediolateral axis at MTP joint	Spring, planter gear mechanism	0 : 30°	Coupling	Aluminum
Belgium	The AMP-foot 2.0 (2013) [26, 27]	2.5 kg	Lever arm and spring combined mechanism	1 DC motor	Mediolateral axis at MTP joint	Springs and SEA	0 : 45°	Prosthesis ankle joint	Aluminum
United Kingdom	Virtual prototyping of a semiactive transfemoral prosthetic leg (2015) [28]	2.3 kg	Springs	1 DC motor	Mediolateral axis at MTP joint	SEA and springs	N/A	Nut and bolt	N/A
Italy	Variable compliant humanoid foot (2016) [29]	0.52 kg	Leaf springs, cam followers based method	1 DC geared motor	Longitudinal axis of the foot	Leaf spring, motor actuated	N/A	Humanoid ankle	Aluminum, rubber
China	Bioinspired tunable stiffness robotic foot (2017) [30]	N/A	Spring	Stepper motor	Mediolateral axis and longitudinal axis	Spring and ball screw	N/A	Ball joint	N/A

Table 7: Results of keyword search in respective academic databases.

Keyword	IEEE Xplore	Elsevier	SAGE	InTech	PLOS ONE	ASME
Foot/feet	7,539	120,657	101,738	1,478	2,876	149
Lower limb prosthesis	267	12,434	2184	244	10,201	35
Humanoid robots	11,404	2,276	707	772	3,693	7
Ankle-foot prosthesis	48	3,864	865	244	880	25
Adaptive foot prostheses	354	1,992	148	61	237	399
Artificial limb	1404	26,272	3,496	691	37,951	50

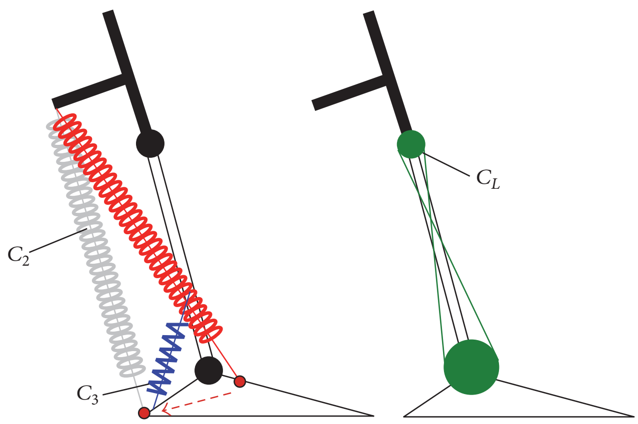


Figure 7: Spring arrangement of fully passive transfemoral prosthesis [9].

torque, joint power, and force variation for gait cycle for proving the prototype functionality.

5.2. Fully Passive Transfemoral Prosthesis Prototype [9]. Fully passive transfemoral prosthesis (Figure 8(b)) was developed by the University of Twente, Enscheda, Netherlands, in 2011. The adaptive foot prosthesis part is designed as spring-based linkage mechanism. The energy storing mechanism using springs is as in Heel Foot [8]. In this prosthesis adaptive foot manoeuvres with the aid of knee and ankle generating potential energy. During the stance phase, both knee and ankle absorb a certain amount of energy for carrying body weight. Then knee further absorbs energy for preswing and the ankle generates 80% of total energy for push-off. With the analysis of gait power requirement diagrams, this paper suggests that the knee is more like an energy absorber and ankle is more like an energy generator. This concept was the intuition for the conceptual design shown in Figure 7.

Two springs are crossed to each other and connected to ankle. During the preswing phase, knee absorbs the kinetic energy and stores it in C_L spring. Then when the swing phase arrives kinetic energy will be stored in C_2 spring. Stored energy during swing phase can be reused in stance phase while C_3 spring stored kinetic energy can be used in the next stage. Spring arrangement in the proposed mechanism is shown in Figure 7. Cable mechanism is used to govern the ankle and adaptive foot bends according to the knee flexion during the gait cycle. The conceptual design did not simulate. The prototype has been developed. However, prosthesis did not validate.

5.3. Passive Slope Adaption Prosthetic Ankle-Foot System [10]. This mediolateral direction rotating single DoF passive device was developed by a set of researchers from USA (Figure 8(c)). This prosthesis consists of link and cam on the passive ankle joint and the foot plate moves according to the slope of the surface. The moving range of the joint is only 18°. The prosthesis is validated with a set of experiments and the system has no energy regeneration method and comparatively the surface adaption mechanism is a basic method with a limited range of motions.

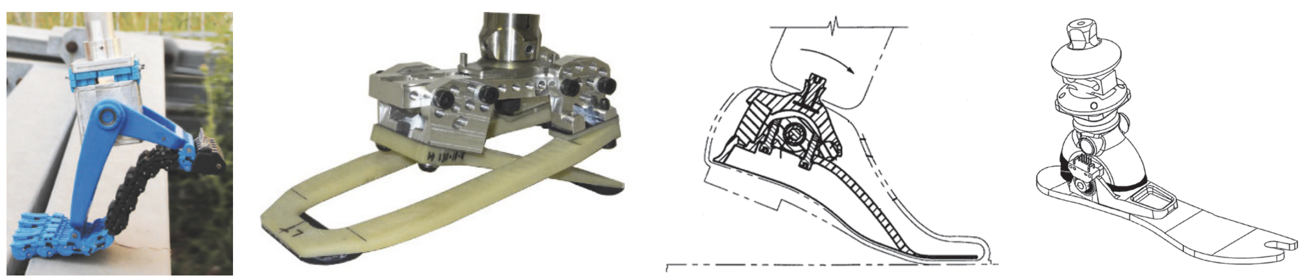
5.4. Bipedal Walking Robot with Oblique Midfoot Joint in Foot [11]. This foot was developed by a group of Japanese researchers in 2015. The bipedal walking robot in Figure 8(d) was developed to generate the adaptive nature of the foot with midfoot axis rotation nature. Oblique axis DoF foot prostheses are rarely used in foot prostheses due to the lack of strength. The bipedal walking robot is a humanoid robot that has been designed to replicate the human foot motions. The tendon wire mimics the arch of the foot. Yet the weight carrying capacity is limited in this design.

5.5. SoftFoot [12]. SoftFoot (Figure 9(a)) has been developed to improve the adaptive nature of the foot prosthesis. This is a complete passive foot prosthesis developed by studying the human foot arch and bone arrangement along the longitudinal direction. The prototype was developed by Research Center "Enrico Piaggio," University of Pisa, Italy, in 2016 using a rapid prototype method. SoftFoot was developed based on windlass mechanism [45]. Chain of connectors which can rotate parallel to mediolateral direction is used as foot links. The foot arch angle is fixed and no energy regeneration method is available with SoftFoot. The SoftFoot was validated with a compliant simulation for load distribution. Also the experiments were carried out to measure the performances on uneven terrains. The device was validated by comparing the surface adaption capability with a rigid flat foot.

5.6. Hindfoot and Forefoot Stiff Foot Prostheses [13]. This passive stiff foot prosthesis shown in Figure 9(b) was developed in the USA in 2017. The device consists of a rubber base which enables the prosthesis to function the push-off movement of the foot with varying arch and windlass mechanism. This

(a) (b) (c) (d)

Figure 8: Passive foot prostheses. (a) The Heel Foot [8], (b) fully passive transfemoral prosthesis prototype [9], (c) prosthetic ankle-foot system [10], and (d) bipedal walking robot with oblique midfoot joint in foot [11].



(a) (b) (c) (d)

Figure 9: Passive foot prostheses. (a) SoftFoot [12]. (b) Hindfoot and forefoot stiff foot prostheses [13]. (c) One-piece mechanically differentiated prosthetic foot [14]. (d) Instrumented prosthetic foot [15].

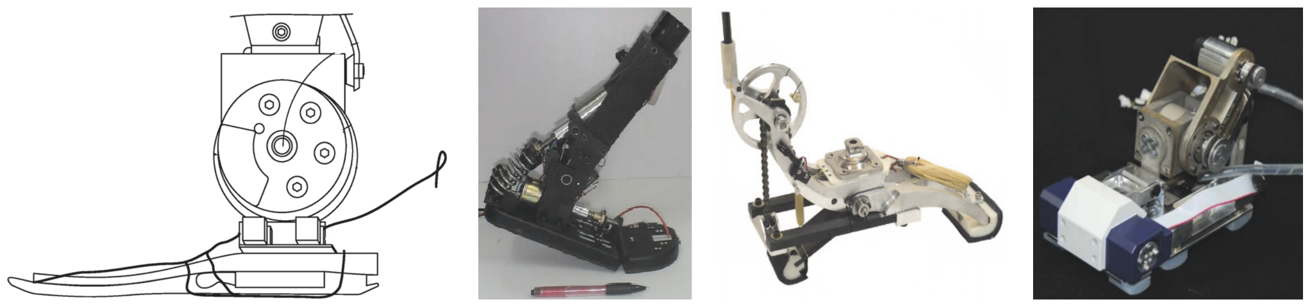
design has been validated and results have proved the compatibility of implementing it to an actual passive device.

5.7. One-Piece Mechanically Differentiated Prosthetic Foot [14]. This is one of the passive-adaptive foot prosthetic devices available in the patent database. These types of passive feet are very much similar to flat prosthetic feet. However, this foot prosthesis is fabricated by lightweight polymeric material which enables the foot flex on any surface. This device has been developed for ankle disarticulated amputees. Due to the material type and contact surface it has the limitation of walking along the rough uneven surface. Limitation of the bend along the longitudinal axis is another problem in this design. Load carrying capacity is limited due to the type of material used for this device. Figure 9(c) shows the design of this passive foot prosthesis which was patented in 1997.

5.8. Instrumented Prosthetic Foot [15]. The instrumented prosthetic device is a passive foot prosthesis which was developed by USA research team in 2012. This device is to be fitted to a lower-limb ankle controlled by sensors. Ankle prosthesis is connected to foot via a pyramid connector. This is made of a polymer material known as durometer polyurethane. Surface adaption of this prosthesis is obtained by the stiffness of the polymer material (refer to Figure 9(d)).

5.9. PANTOE 1 [17, 18]. PANTOE 1 is one of the advanced, energy regenerative active prostheses with mediolateral direction rotation. It has 1-DoF ankle and 1-DoF foot segment. It was developed by College of Engineering, Peking University, Beijing, China, in 2010 (refer to Figure 10(b)). PANTOE 1 consists of two series elastic actuators (SEA). SEA is one of the high torque generating actuation methods available in modern prosthesis world. Foot segment is actuated with one DC brush motor, ball screw, and SEA. PANTOE 1 was controlled by finite state control method [11] and the system was validated based on control method. The foot prosthesis segment lacks the adaption capability as PANTOE foot segment has 1 DoF. Adaption along the longitudinal axis is lacking in this design.

5.10. Universal Prosthesis Emulator [19]. This foot prosthesis was developed by Carnegie Mellon University, Pittsburgh, USA (Figure 10(c)). This prosthesis can bend through mediolateral joint the same as the human MTP joint. The significant difference compared to other prostheses is a user of chain mechanism to control foot arch angle and emulator based high-performance software environment use to control the prosthesis. This is an active foot prosthesis which has the ability to perform plantar flexion. 1.61 kW AC servo motor is used to control the arch angle of the prosthesis to maintain the stability. In this design while the prosthesis is at heel strike



(a) (b) (c) (d)

Figure 10: Active and hybrid foot prostheses. (a) Ankle-foot prosthesis of automatic adaptation [16], (b) PANTOE 1 [17, 18], (c) universal prosthesis emulator [19], and (d) parallel four-bar linkage humanoid robot [20].

(a) (b) (c) (d)

Figure 11: Developed foot prostheses. (a) Energy recycling foot [21, 22]. (b) Adaptive bipedal deformable feet [23]. (c) An adaptive sensor foot for a bipedal and quadruped robot [24]. (d) The AMP-Foot 1.0 [25].

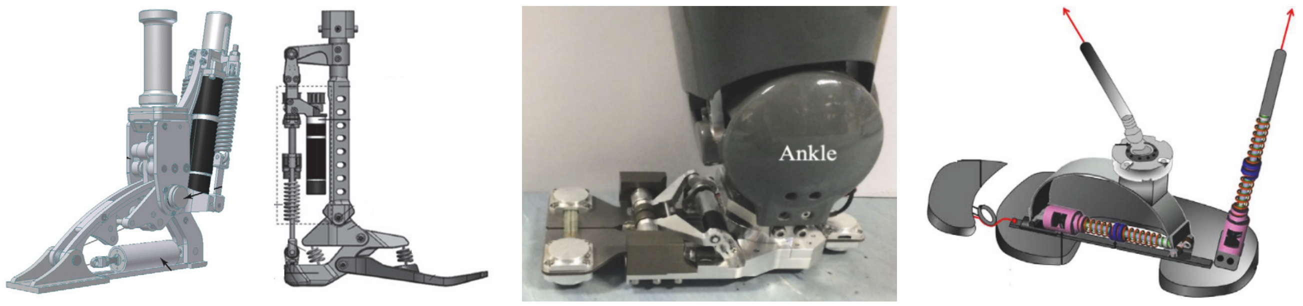
phase, passive heel spring bends and stores energy and pulley rotates to cause tension to the chain which is connected to passive heel to the other end.

As it is in Table 4, prostheses weighted around 1 kg range which is around average human foot weight [44, 45]. The majority of prostheses rotate along the transverse axis with no foot with a degree of freedom along both axes. Spring-based mechanisms are popular as an energy regenerative method. The motion ranges are closely following actual human joint ranges (Table 1). Lack of proper attachment methods to amputees can be seen in the majority of these designs. Aluminum and carbon fiber materials are more common due to the high strength and lightweight in the majority of these designs. Some foot prostheses have validated joint torques, forces, and angle for gait cycle [8, 9, 20] yet few simulated design performance [12].

5.11. Parallel Four-Bar Linkage Humanoid Robot [20]. Humanoid robots are too generating human foot motion. This 1-DoF humanoid (Figure 10(d)) was developed by the University of Tokyo, Japan, which attempted to mimic the toe joint motion through MTP joint of the human foot. Two parallel links have been used to connect to the toe link and foot link and developed four-bar parallel linkage mechanism. A DC servo motor (Maxon RE-max 17, 2.5 W) is used to control the toe mechanism. Toe-off can undergo maximum torque of 590 mNm. Three-axis force sensor has been attached to the base of the forefoot to detect ground reaction force and prevent the maximum torque. According to the validation results, toe-off motion can be performed with this mechanism and the toe can bend up to 44° while human MPT joint can bend about 40°.

5.12. Energy Recycling Foot [21, 22]. The University of Michigan, USA, developed this energy harvesting active prosthetic foot (Figure 11(a)) in order to introduce the control energy storage and return concept. This is a single active DoF prosthesis that stores the energy into springs and locks it during gait phase and releases it under clutch motor control based on sensory inputs. There are two DC electric motors to rotate the toe and heel. Force sensors connected to forefoot work as sensors which capture energy during heel contact phase and release it at toe-off phase. According to the validation results, this prosthesis has reduced net metabolic energy expenditure by 23% compared to normal walking.

5.13. The AMP-Foot 1.0 [25]. The AMP-Foot 1.0 was designed by the Department of Mechanical Engineering, Vrije Universiteit Brussel, Brussels, Belgium, in 2012 (Figure 11(d)). This was an initial design with a flat foot, yet with spring, locking mechanism, and planetary/epicyclical gear system to control the movement of joint. The locking mechanism was the



(a) (b) (c) (d)

Figure 12: Developed foot prostheses. (a) The AMP-Foot 2.0 [26, 27]. (b) Virtual prototyping of a semiactive transfemoral prosthetic leg [28]. (c) Variable compliant humanoid foot [29]. (d) Bioinspired tunable stiffness robotic foot [30].

intuition for developing the AMP-Foot 2.0 [26, 27] later with foot mechanism. This design was validated experimentally to prove the functional capability of ankle foot.

5.14. The AMP-Foot 2.0 [26, 27]. This is a further development of AMP-Foot 1.0 [25] with energy regeneration adaptive foot (Figure 12(a)). Plantarflexion spring stores energy and regenerates the same as in other active foot prostheses. Two force sensing resistors are used as input sensors to detect the surface contact. The mechanism consists of lever mechanism to control the energy storing. AMP-Foot 2.0 is at the development stage and only the design was available. Simulated results were available based on the design. Lever and locking mechanism is novel in this design compared to other existing foot prostheses.

5.15. Variable Compliant Humanoid Foot [29]. This is another human foot in humanoid robots which was developed by the Department of Advanced Robotics, Istituto Italiano di Tecnologia, Italy, in 2016 (Figure 12(c)). The significance in this development is that it can adapt along the longitudinal axis of the foot. The variable compliant humanoid foot is an active robot that consists of small geared motor (Maxon), 6-axis force/torque sensor, leaf springs, and rubber ball with pressure sensors. Cam with leaf springs connected to transverse axis store energy when the toe leaf spring bends along the longitudinal axis. The humanoid robot was validated for motion experiments as well as spring stiffness experiments to prove the design functionality. Longitudinal adaption is the significance in this design. Some existing foot prostheses [25–27] and humanoid robots [20] use electronic sensor inputs to control motions.

6. Discussion and Future Directions

The anatomical structure of the human foot has been studied from a biomechanical perspective prior to the review of design and development. Several existing adaptive foot prostheses were reviewed in this paper upon different design criteria. Subsequently, the requirements and design difficulties were identified. In this paper, adaptive foot prostheses were classified as passive, active, and hybrid based on actuation method. The key parameters of existing adaptive foot prostheses were compared in Tables 4, 5, and 6 by indicating their country of origin, references, weight, actuation method, the axis of rotation, type of mechanisms used, movable ranges, attaching method to the remaining prosthesis or residual limb, and used materials.

The human foot consists of complex sets of joints. It undergoes significant impulsive force throughout the gait cycle due to the body weight and ground reaction force. It is essential to develop a device with the strong and lightweight material. Novel mechanisms and high torque lightweight actuators are necessary for adaptive foot prostheses to reduce the weight. Total weight of the device needs to be approximately closer to average human foot weight to avoid the baring of unnecessary weight. Most of the existing adaptive foot prostheses are 1 DoF or 2 DoF and can only be rotated along MTP joint. Only a few prostheses have the rotation capability along the longitudinal axis. Thus designing and developing an adaptive foot prosthesis which can be movable along both axes are a challenging task. Yet such development will improve the stability of lower-limb prostheses on any uneven terrain.

High torque-to-weight ratio actuators are essential for high-performance adaptive foot prostheses. The joint sizes are smaller and total number of joints is larger in the toe region of the human foot. Therefore miniature actuators are needed to actuate multiple DoF in the toe region. Currently available shelf actuators do not fulfil this requirement. Few developers have overcome this issue to a certain extent by using customized actuators. Yet, it is a costly method for small scale researches.

In order to reduce the external power usage and regenerate the power, mechanisms such as SEA, coil springs clutch motors, and springs can be used as actuators. These mechanisms can store the energy and release energy repetitively throughout the gait cycle. Additionally, spring effect enables the adaptive nature up to a certain extent. Furthermore, research needs to be carried out to develop energy regeneration. Authors foretell that future adaptive prostheses will consist of energy regenerative methods and will be more convenient for users.

As for not to feel discomfort by the amputees in long-term prostheses usage, attaching method of adaptive foot prosthesis to the lower-limb or to residual limb is crucial. Therefore, further research needs to be carried out to develop ergonomically friendly attaching sockets. Ultimately these robotic devices are to be used by humans as an artificial body part. Hence mechanical stoppers and control based safety precautions and manual maneuvering methods are necessary to be included for prostheses.

Prosthesis designs should fulfil the anatomical demands as well as the physiological demands of users. Adaptive foot prostheses are necessary to have an attractive elegant appearance with the portable facility. Some of the existing adaptive foot prostheses have managed to fulfil several of the above-mentioned design requirements, although none of them has combined all the essential functionalities to a single device. Most existing adaptive foot prostheses have limited torque, power, and ranges of motion. Unnecessary noise and vibration reduce the quality of device further. These general issues have to be addressed in future designs.

7. Conclusion

This review summarized existing design criteria of adaptive foot prostheses in order to develop an adaptive foot prosthesis. In this paper, systematic literature search approach was adopted. The scope of this paper, which is the adaptive nature of foot prostheses, has not been discussed in available review papers. This paper presented design classification parameters for each classification method of existing adaptive foot prostheses. In modern days, active and hybrid prostheses are more popular due to their high functional capabilities. Yet, in this paper some of the existing passive-adaptive foot prostheses have also been reviewed due to their significance in mechanisms and the possibility of transferring such mechanisms to hybrid devices. The adaptive foot prostheses have been classified based on actuation method and compared considering design requirements and design criteria. It enables the reader to compare and contrast the existing devices and choose the most appropriate method for their design requirements.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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