

REVIEW

The Categories of AFO and Its Effect on Patients With Foot Impair: A Systemic Review

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There are a lot of ailments that would lead to foot impair. For instance, cerebral palsy (CP), stroke, multiple sclerosis (MS), hemiplegia, duchenne muscular dystrophy (DMD) and so on. With the further deterioration of these diseases, gait would become imbalanced and then it may contribute to high risk of fall incidence. Thus, it is urgent to invent a tool to adjust the foot impair. Most of the previous studies had found that the ankle-foot orthoses (AFO) has a significant effect to overcome the foot impair. Studies that investigated the ankle-foot orthoses (AFO) and its effect on patients with foot impair are various and abundant. Nevertheless, there are a little studies that integrated the categories of AFO and its specific effect on patients with foot impair. It is important to integrate the categories of AFO and its specific effect on patients with foot impair because the previous studies had proved that different designs of AFO have different mechanical properties and these would affect outcomes in a way. The purpose of this paper is to review and integrate the published studies on the categories of AFO and its effect on patients with foot impair and thereby offer better guidelines and suggestions for prescriptions and future studies. The publication of all papers about the categories of AFO and its effect on patients with foot impair were obtained from Science Direct(SD), Google Scholar and other peer reviewed journals that were published in English. The keywords used for searching were "AFO," "material," "foot impair," and "systemic review." There were total 8647 studies regarding these keywords, and 37 studies were eligible to be selected in this research: 2 studies on systemic review, 35 studies on the materials and categories of AFO and its effect on patients with foot impair. Most previous studies had found that the effect of AFO is related to mechanical properties of AFO and disease characteristics. Therefore, this review could provide researchers with more systemic and detailed information about the categories of AFO and its effect on patients with foot impair and promote synthesis of literature.

Keywords: ankle-foot orthoses (AFO); material; foot impair; systemic review

1. Introduction

Legs are essential parts of body which can promote walking movement from one place to another (Hamid, Patar, & Ayub, 2012). The inability to walk normally affects one's life adversely. In patients with foot impair, which is caused mostly by central neurological disorders, such as cerebral palsy (CP), stroke, multiple sclerosis (MS), hemiplegia, duchenne muscular dystrophy (DMD) and so on (Hamid et al., 2012), gait would become imbalanced and then it may contribute to high risk of fall incidence.

There are two types of people who are more likely to suffer from these ailments, children and the elderly. Once they are attacked by these diseases, their plantar flexor muscles would become weaker and weaker. And then, the ability to push off with the ankle may be mostly reduced (Bregman, Harlaar, Meskers, & de Groot, 2012); (Waterval, Harlaar, Nollet, & Brehm, 2016). These diseases may also cause calf muscle weakness, which is typically characterized by excessive ankle dorsiflexion during stance phase, and this would force the knee into persistent flexion (Waterval et al., 2016); (Ploeger, Bus, Brehm, & Nollet, 2014). Accordingly, the moment of the external knee flexion would be prolonged (Ploeger, Bus, et al., 2014). These muscles are

also significant parts of body to provide stability for ankle and knee during single limb support in walking (Ploeger, Bus, et al., 2014); (T. Kobayashi, Leung, Akazawa, & Hutchins, 2011). Also, Patients who suffered from these diseases would spend higher energy and experience more falls than healthy people when walking in daily lives, which is a dangerous health issue especially in the geriatric population (Bregman et al., 2012); (Ploeger, Bus, et al., 2014). They would get a vicious circle over time, and ultimately, they would lose the ability to walk. The ankle-foot orthoses (AFO) is a medical device that can correct foot impair or prevent impair progression, improve walking ability through limiting unnecessary and abnormal motion, keep lower limb joint stability and strengthen lower limb weight-bearing capability (Tang, 2008). A wide variety of AFO were employed on patients with foot impair, and different patients had presented diverse effect after using AFO. Thus, the aim of this paper is to review and integrate the published studies on the categories of AFO and its effect on patients with foot impair and thereby offer guidelines and suggestions for prescriptions and future studies.

2. Methods

2.1. Search strategy

An electronic search of the published studies was performed to offer an integrated review regarding the categories of AFO and its effect on patients with foot impair, using these databases below: Science Direct(SD), Google Scholar and other peer reviewed journals that were published in English. The search was conducted using the terms related to "AFO," "material," "foot impair," and "systemic review." The published studies on the Gait & Posture journal were all selected for next filter. There were no subjects in this research.

2.2. Inclusion Criteria

All papers (from 2000 to 2017 years) retrieved by the search strategy regarding the keywords above were included. Subsequently, studies were selected from these papers if they explored the categories of AFO, evaluated the effect of AFO on patients with foot impair that is caused by cerebral palsy (CP), stroke, multiple sclerosis (MS), hemiplegia, duchenne muscular dystrophy (DMD) and so on (Hamid et al., 2012); (J. Romkes, Hell, & Brunner, 2006) and provided biomechanical data on the gait performance of patients suffered from these diseases. Following, only papers from peer reviewed journals which were published in English, such as Gait & Posture, were included in this research.

2.3. Data Extraction

The full text of studies identified from the search were reviewed and integrated one by one. The data of these studies including study characteristics (purposes, population, and methodology), the materials and categories of AFO and their effect on patients, especially the biomechanical effect, was extracted from these studies.

3. Results

Approximately 8647 papers searched from databases were related to these keywords. Subsequently, 37 studies were included in this review according to their abstracts and the inclusion criteria: 2 studies on systemic review, 35 studies on the materials and categories of AFO and its effect on patients with foot impair (Mustapa, Justine, Mustafah, Jamil, & Manaf, 2016); (Ridgewell, Dobson, Bach, & Baker, 2010).

3.1. Study Characteristics

For all the studies selected in this review, the primary and most important purposes were to explore the effect, especially the biomechanics effect, of one or some kinds of AFO on patients with foot impair and offer guidelines and suggestions for clinicians and future studies. The population in these studies were patients suffered from foot impair, which is caused by cerebral palsy (CP), stroke, multiple sclerosis (MS), hemiplegia, duchenne muscular dystrophy (DMD) and so on (Hamid et al., 2012); (J. Romkes et al., 2006). Most of them are children and the elderly who are easier to be attacked by these ailments. The data of gait performance and the biomechanical effect on the patients were mostly assessed using a three-dimensional(3D) eight-camera VICON motion capture system operating at a sample rate of 100 Hz (VICON, Oxford, UK), with participants wearing the customized AFO or shoes only, walking on the ground or the treadmill for several times. For both situations, several trials with participants precisely hitting the force plate were extracted for analysis (Leardini, Aquila, Caravaggi, Ferraresi, & Giannini, 2014). The energy cost of walking was assessed during a 5 to 10 min walk test at the self-selected speed (Bregman et al., 2012); (Ploeger et al., 2012). The

energy cost of walking, which is often defined as the normalized net oxygen cost of walking, is calculated by dividing the net oxygen consumption by speed and body mass (Bregman et al., 2012). Subsequently, the data of gait performance and the biomechanical effect on the patients extracted from the three-dimensional (3D) eight-camera VICON motion capture system were processed using Visual3D (C-motion, Germantown, MD, USA) or/and Excel (Toshiki Kobayashi et al., 2017).

3.2. The materials and categories of AFO

The ankle-foot orthoses (AFO) is a medical device that can correct foot impair or prevent impair deterioration, improve walking ability through limiting unnecessary and abnormal motion, keep lower limb joint stability and strengthen lower limb weight-bearing capability (Tang, 2008). When walking with AFO, patients would perceive more safety and stability and less fatigued than walking with shoes-only. As a significant part of treatment (Tang, 2008), AFO has become more and more important.

A wide variety of AFO were employed on patients with foot impair. In general, AFO can be classified into two categories: the non-articulated AFO or the thermoplastic AFO, which has the fixed stiffness and joint that were determined in the fabrication, fitting and adjustment processes; the articulated AFO, which has a flexible mechanical joint (Leardini et al., 2014); (Toshiki Kobayashi et al., 2017); (Radtka, Skinner, & Elise Johanson, 2005); (Jacqueline Romkes & Brunner, 2002); (Bartonek, Wang, Eriksson, & Gutierrez-Farewik, 2013). These two AFO have their own advantages.

The AFO also has some weaknesses. For one thing, the AFO may limit lower limb muscle activities in a way after long time with it (Tang, 2008); (Radtka et al., 2005). For another, some kinds of AFO are bulkier and heavier (T. Kobayashi et al., 2011); (Ploeger et al., 2012) because of the materials and some other things. Patients who wearing these AFO would feel uncomfortable when walking in daily lives. When AFO was developed originally, almost all the materials used on AFO were uniform. They were hard and brittle, and easy to be damaged, and did not have good elasticity (Ploeger, Brehm, Bus, & Nollet, 2015). Additionally, the categories of AFO were also limited, the same AFO were almost applied on all patients with foot impair, no matter of causes that led to foot impair. However, with the development of technology and biomechanics, the structures and materials of the AFO have been improved considerably, the customized, multifunctional, suitable ankle-foot orthoses has come out (Tang, 2008). For instance, the energy-storing, spring-like carbon-composite Ankle Foot Orthoses (Bregman et al., 2012); (Radtka et al., 2005); (Ploeger et al., 2015); (Alvela et al., 2015); (Meyns et al., 2016); (Kato, Maeda, & Murakami, 2012), which can reduce the energy cost of walking by replacing a substantial part of the ankle work; the active ankle foot orthosis (AAFO), which can control critical ankle motion during dorsiflexion and plantarflexion automatically through using the flexiforce sensor (Hamid et al., 2012); (Ploeger et al., 2012); (Cruz & Dhaher, 2009), rather than adjust it manually. More and more high polymer materials are devoted to the fabrication of AFO (Tang, 2008). Such as polypropylene, polyethylene, carbon fiber and their composites (Ploeger et al., 2015); (Meyns et al., 2016); (Ridgewell, Rodda, Graham, & Sangeux, 2015); (Dufek, Neumann, Hawkins, & O'Toole, 2014); (Sabbagh, Fior, & Gentz, 2016). Before solidification, the high polymer materials are easier to model because it is soft enough, and it will have good stiffness and tenacity after modeling. What's more, light weight, comfortable and convenience are also virtues of the high polymer materials.

3.3. The effect of AFO on patients with foot impair

3.3.1. Spatio-temporal variables

The step length and cadence may increase marginally according to the conditions of patients after using AFO (Ploeger et al., 2012); (Nikamp et al., 2017). The timing of toe-off and the timing of contralateral heel strike may decrease marginally (Nikamp et al., 2017); (Böhm, Braatz, Hösl, & Döderlein, 2015). However, Theresa Hayes Cruz et al. (2009) had argued that there was no difference of the step length between AFO and no AFO conditions (Cruz & Dhaher, 2009). D.J.J. Bregman et al. (2014) had demonstrated that the timing of toe-off and the timing of contralateral heel strike were not changed as a result of wearing the AFO (Bregman et al., 2012). Future studies in a large sample of patients with foot impair should further explore the spatio-temporal variables.

3.3.2. Kinematics and Kinetics

The main effect of ankle-foot orthoses on patients with foot impair is concentrated on controlling the motion of ankle. Significant effect of AFO on patients with foot impair were found almost on all ankle Kinematic and Kinetic parameters. The range of motion of ankle would significantly decreased as a result

of wearing the AFO (Bregman et al., 2012); (Waterval et al., 2016); (T. Kobayashi et al., 2011); (Radtka et al., 2005). In patients with foot impair, the plantar flexor muscles would be weaker, which led to the reduced ability to push off with ankle (Bregman et al., 2012); (T. Kobayashi et al., 2011). The AFO can overcome the reduced ankle push-off. Previous studies had shown that the AFO can control excessive ankle dorsiflexion to improve knee extension (Waterval et al., 2016). The AFO took up a massive part of the ankle moment and the peak ankle moment increased considerably when walking with the AFO (Nikamp et al., 2017); (Böhm et al., 2015).

Some of previous studies had demonstrated that the hip and knee kinematics and Kinetics were not significantly different between the AFO and no AFO conditions (Bregman et al., 2012); (Cruz & Dhaher, 2009). However, Corien D.M. Nikamp et al. (2017) had found that the knee and hip flexion at initial contact increased significantly with AFO (Nikamp et al., 2017). And also, Ploeger Hilde E. et al. (2017) had found that knee extension during mid-stance increased after using AFO (Ploeger, Bus, et al., 2014). The effect of AFO on the hip and knee kinematics and kinetics varied between papers. It is vital for future studies in a large sample of patients with foot impair to determine whether the AFO would affect the hip and knee kinematics and kinetics and what is effect of AFO on it?

3.3.3. Energy cost of walking and walking speed

Patients who suffered from foot impair would spend more energy when walking in daily life, and their walking speed would become slower and slower with the deterioration of their ailments (Bregman et al., 2012); (Ploeger et al., 2012); (Meyns et al., 2016); (Kato et al., 2012); (Kerkum, Harlaar, et al., 2015). Previous studies had showed that the energy cost of walking would be significantly reduced and walking speed increased considerably after using some kinds of AFO for some time. Ploeger Hilde E. et al. (2014) had demonstrated that change in walking energy cost was not significantly associated with any of the biomechanical gait parameters (Ploeger, Bus, et al., 2014).

The following (**Table 1**), which was integrated from the selected studies for this review, showed the materials and categories of modern AFO and their effect on patients with foot impair.

4. Discussion

This systemic review assessed 37 full studies, exploring the materials and categories of AFO and its effect on patients with foot impair. There are a large number of studies published on peer reviewed journals that evaluated the materials and categories of AFO and their effect on patients with foot impair, and different effect on patients with foot impair was found between various types of AFO (Schmalz & Pröbsting, 2015); (Neviani, Borghi, Costi, & Ferrari, 2013); (Lam, Leong, Li, Hu, & Lu, 2005).

The gait biomechanical properties, the energy cost of walking, the speed of walking and the stability of stand or walking are the main study points of effect that AFO acts on patients with foot impair. In general, correcting foot impair or preventing impair deterioration, improving walking ability through limiting unnecessary and abnormal motion, keeping lower limb joint stability and strengthening lower limb weight-bearing capability are common effect on patients with foot impair through wearing AFO (Tang, 2008); (Ridgewell et al., 2015); (Heintz, 2014). But different kinds of AFO have different special emphases according to their unique mechanical properties. For instance, the energy-storing, spring-like carbon-composite Ankle Foot Orthoses (Bregman et al., 2012); (Radtka et al., 2005); (Ploeger et al., 2015); (Alvela et al., 2015); (Meyns et al., 2016); (Kato et al., 2012); (Neviani, Borghi, Costi, & Ferrari, 2012) devote to reduce the energy cost of walking, and the active ankle foot orthosis (AAFO) (Hamid et al., 2012); (Ploeger et al., 2012); (Kerkum, van den Noort, et al., 2015) is prone to control critical ankle motion during dorsiflexion and plantarflexion automatically through using the flexiforce sensor, rather than adjusts it manually. On account that each patient has his own gait pattern and symptom, the effect of AFO seems to vary between patients (Westberry et al., 2007); (Haight, Russell Esposito, & Wilken, 2015); (Hyun, Kim, Han, & Kim, 2015); (van Beeten, Hartman, & Houdijk, 2015); (Ries & Schwartz, 2015); (Sabbagh, Fior, & Gentz, 2014). Therefore, it is crucial for a clinician to select an optimal AFO for patients after fully understanding the causes and symptoms of patients. Future studies in a large sample of patients with foot impair should further explore the unique mechanical properties of each AFO and its effect on target population. What's more, it is vital to investigate the potential of optimizing AFO's materials and mechanical properties to maximize the improvement in outcomes in patients with foot impair.

Table 1: The materials and categories of modern AFOs and their effect on patients with foot impair.

Author	Ailment	Category	Material	Characteristic	Effect
W. Bromwich et al. (2011) (Bromwich, James, Stewart, Emery, & Quinlivan, 2012).	Patients with duchenne muscular dystrophy (DMD).	AFO footwear combination (AFOFC)	Carbon composite	Adjustable ankle hinges	<ol style="list-style-type: none"> 1. Improved walking distance; 2. Reduced step width and double support time; 3. Increased walking speed and step length; 4. Decreased anterior pelvic tilt; 5. Reduced calf pain; 6. Near normal range of motion at the knee; 7. Knee valgus moments normalised to varus moments; 8. Reduced plantarflexion contracture.
D.J.J. Bregman et al. (2012) (Bregman et al., 2012); H.E. Ploeger et al. (2015) (Ploeger et al., 2015); Ása Bartonek et al. (2013) (Bartonek et al., 2013); M. Alvela et al. (2015) (Alvela et al., 2015); Y. Kerkum et al. (2015) (Kerkum, Harlaar, et al., 2015).	Patients with multiple sclerosis, stroke.	Energy-storing, spring-like carbon-composite Ankle Foot Orthoses	Carbon composite	Energy-storing, spring-like properties	<ol style="list-style-type: none"> 1. Reduced energy cost of walking and supported the reduced ankle push-off power; 2. Increased walking speed; 3. Increased stride length and cadence marginally; 4. Decreased the range of motion of the ankle significantly; 5. Reduced mean plantar flexion velocity during push-off; 6. Increased the peak ankle moment.
Ploeger Hilde E. et al. (2014) (Ploeger, Brehm, et al., 2014); H.E. Ploeger et al. (2011) (Ploeger et al., 2012).	Polio survivors with calf muscle weakness.	Dorsiflexion-restricting ankle-foot orthoses (DR-AFOs)	Carbon composite	Dorsiflexion-restricting	<ol style="list-style-type: none"> 1. Increased forward progression of the center of pressure (CoP) in mid-stance; 2. Reduced ankle dorsiflexion and knee flexion in mid- and terminal stance; 3. Reduced energy cost of walking; 4. Increased walking speed.
Toshiki Kobayashi et al. (2017) (T. Kobayashi et al., 2011); A. Leardini et al. (2014) (Leardini et al., 2014).	Patients with post-stroke.	An articulated ankle-foot orthosis with adjustable plantarflexion resistance, dorsiflexion resistance and alignment	4.8 mm thick polypropylene homopolymer	Adjustable plantarflexion resistance, dorsiflexion resistance and alignment	<ol style="list-style-type: none"> 1. Improvement in heel rocker (1 st rocker); 2. Increased walking speed; 3. Reduced the peak released ankle power; 4. Stabilized knee joints in stance; 5. Showed a systematic change in moment-angle relationship when plantarflexion resistance, dorsiflexion resistance and alignment were changed; 6. The ankle and knee joint kinematics and kinetics also showed some systematic changes in response to changes in mechanical properties of the AFO during gait; 7. The knee moment appeared more responsive than the knee angle to the changes in AFO's mechanical properties.

(contd.)

Author	Ailment	Category	Material	Characteristic	Effect
Aminuddin Hamid et al. (2012) (Hamid et al., 2012); Rishabh Kochhar et al. (2016) (Kochhar, Kanthi, & Makkar, 2016); T. Schmalz et al. (2016) (Schmalz & Pröbsting, 2015).	Patients with spinal cord injury, stroke and trauma.	Active ankle foot orthosis (AAFO)	/	Equipped with a controller which controls critical ankle motion during dorsiflexion and plantarflexion.	1. Handled a foot movement smoothly similarly normal gait pattern; 2. By using flexiforce sensor, the timing to moving actuator is based on real time approach.
Toshiki Kobayashi et al. (2011) (T. Kobayashi et al., 2011).	Patients with stroke hemiplegia.	An experimental AFO (EAFO)	composite	Adjustable stiffness	1. Reduced mean peak plantarflexion angle; 2. Reduced the mean peak dorsiflexion angle; 3. Assisted the heel rocker function during loading response; 4. Controlled the range of motion of the ankle joint.
E. Ridgewell et al. (2015) (Ridgewell et al., 2015).	Patients with cerebral palsy (CP), hereditary spastic paraplegia (HSP), spina bifida (SB).	Bilateral solid AFO	/	/	1. Reduced Ankle dorsiflexion; 2. Increased walking speed; 3. Increased step length; 4. Increased cadence.
Daniel Sabbagh et al. (2016) (Sabbagh et al., 2016).	Patients with cerebral palsy following ischemic perinatal stroke.	A dynamic AFO	Carbon composite	Adjustable range of motion, defined pivot point.	1. Increased step length, velocity and cadence; 2. Longer single-supported and shorter double-supported phase; 3. Less flexed hip and ankle during stance.
H. Böhm et al. (2015) (Böhm et al., 2015).	Patients with spastic bilateral cerebral palsy.	Solid hinged Ground reaction AFO	/	/	1. Increased walking speed; 2. Reduced ankle plantarflexion strength.

Competing Interests

The authors have no competing interests to declare.

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