Engineering solutions to foot drop

Anatomy and Physiology of Foot Drop

Foot drop occurs from a muscular condition caused by problems with the common peroneal nerve, or paralysis of the muscles in the anterior region of the lower leg. All of these problems can result from the nerve alone or a consequence of the muscle or spinal cord trauma, abnormal anatomy, toxins or disease. Some of the most common diseases that can cause foot drop include: direct hit to the back of the knee; muscular dystrophy; multiple sclerosis and cerebral palsy. It may also be as a result of a complication in a replacement surgery or knee ligament reconstruction surgery. The dorsiflexors affected by foot drop, the tibialis anterior, extensor digitorum longus and extensor hallucis longus, are all controlled by the deep peroneal nerve. The dorsiflexors allow the body to clear an individual’s foot during the swing phase of the gait cycle and control plantarflexion during the heel strike of the stance phase. The peroneal nerve is paired with the tibial nerve to form the sciatic nerve, connecting from the lumbar and sacrum regions of the spinal cord (L4-S1), through the pelvis and down each leg.
The sciatic nerve has a mixed function since it has motor and sensory neurons so the muscles it supplies can feel and move simultaneously. The ventral rami (anterior branch) of L4-S1 has dorsal branches whose fibres are found in the peroneal nerve. The ventral rami of spinal nerves distribute the nerves to the joints, muscles and skin of the “antero-lateral parts of the trunk”, the limbs and the extremities, such as the hands and feet.[3]

The peroneal nerve divides into superficial and deep branches. The initial region that comes off of the deep branch supplies the tibialis anterior, and the remaining neurones supply the other ankle and foot dorsiflexors.

The peroneal nerve is more susceptible to trauma compared to the tibial nerve due to its funiculi (portions of white matter) being larger and less protected by lack of connective tissue. This nerve also has fewer autonomic fibres which leads to the motor and sensory fibres receiving full impact from external sources which can cause injuries.

Gait Cycle

Foot drop affects the gait cycle of the sufferer by preventing dorsiflexion and the movement of the foot inwards or outwards at the ankle.

The normal gait cycle is as follows:

- **Swing phase (SP):** The period of time when the foot is not in contact with the ground. (or all portions of the foot are in forward motion).
- **Initial contact:** The point in the gait cycle when the foot initially makes contact with the ground via the heel.
- **Terminal contact:** The point in the gait cycle when the foot leaves the ground.

The drop foot gait cycle requires more exaggerated phases.

- **DF Swing Phase:** If the foot in motion happens to be the affected foot, there will be greater flexion at the knee to accommodate the inability to dorsiflex. This increase in knee flexion will cause a stair climbing movement.
- **DF Initial contact:** Initial contact of the foot will not have normal heel-toe foot strike; the foot may either slap the ground or the entire foot may be planted on the ground all at once.
- **DF Terminal contact:** They may be too weak to support their body weight and often need a walker or cane during the contact phase. [14]

Dorsiflexion Importance

Dorsiflexion is the movement of the foot in the upwards direction about the ankle. An AFO provides support to those who are not able to dorsiflex during the gait cycle.

- Dorsiflexion allows functioning without overstressing other joints.
- During the gait cycle, the dorsiflexion allows the foot to pass clear through the swing phase without causing tripping or dragging of the foot.
- The compensation for the dragging resistance and tripping makes it more tiring and requires more energy.
- It is needed for sitting, standing, and other positions and movements.
- It also is needed for balance.

Treatments

Foot drop can be managed by physiotherapy, the wearing of an ankle-foot orthosis (AFO), electrical nerve stimulation or surgery and will be determined based on the nature of the cause.[4][5]

Physiotherapy is normally used when the problem stems from weak muscles; the exercises involved can strengthen ankle muscles and improve symptoms.

The use of an AFO is the most common treatment, which can be used to align the lower leg and also to control the motion of the foot and ankle to improve the gait and provide stability.

Electrical nerve stimulation can be used to stimulate the nerves which control the dorsiflexors muscles that are affected by foot drop.
Surgery may be recommended for younger patients or severe cases as it provides a long-term solution to which permanent movement loss has occurred from muscle paralysis. The procedure will either involve fusing ankle or foot bones together to stabilise the ankle or transfer a tendon from the other, stronger leg muscles to the weaker muscle to pull the foot upwards.

**Engineering Solutions**

**The Mechanical Solution - Ankle Foot Orthosis**

"An AFO is a device that supports the ankle and foot area of the body and extends from below the knee down to and including the foot." The external framework works by providing a support for the foot during dorsiflexion using a rigid "L" shaped frame made from a lightweight polypropylene-based plastic. They are used to:

- Aid or prevent a physical deformity
- Stabilise joints (ankle)
- Reduce pain
- Improve mobility, performance and gait
- Reduce the risk of injury

**How AFOs provide a solution**

AFOs come in four types and while all solve the problem of foot drop, can also serve other roles depending on the nature of the problem:

<table>
<thead>
<tr>
<th>Flexible AFOs</th>
<th>Anti-Talus AFOs</th>
<th>Rigid AFOs</th>
<th>Tamarack Flexure Joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provide good dorsiflexion assistance</td>
<td>Block ankle motion, especially dorsiflexion</td>
<td>Block ankle movements and stabilise the subtalar joint</td>
<td>Provide subtalar stabilisation in ankle while allowing free ankle movement. Depending upon the design it may provide dorsiflexion aid to correct foot drop</td>
</tr>
<tr>
<td>Poor stabilisation of the subtalar joint*</td>
<td>Does not provide good stabilisation for the subtalar joint</td>
<td>May also help control movement of the forefoot.</td>
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</tbody>
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*The subtalar joint - located in the ankle - allows inversion and eversion of the foot, but plays no role in dorsiflexion or plantarflexion(pointing) of the foot.

**Important things to consider in designing an AFO**

- **Stiffness and neutral angle**
  - Requirements of the material -
    - It should be strong and supportive yet be flexible, to improve mobility and support in the leg and foot.

- **Material**

- **Adjustability**
  - The ideal prosthesis will adapt to the persons change in height and weight.
  - This will reduce cost and will mean that it will be more likely to fit better. If it does not fit and the patient does not buy a new orthosis (due..."
An ankle foot orthosis is frequently used to assist gait of patients with a variety of pathologies. This can mean that individual mechanical requirements of the AFO will be different for patients. The flexibility of the AFO is dependent on various design properties such as the wall thickness and trimline around the ankle.

A study\(^{[16]}\) showed the influence of stiffness and the initial constructed ankle angle of an AFO on the various muscle activations during the gait cycle. It was observed that the total muscle forces decreased with increasing AFO stiffness.

Varying neutral angle when the neutral ankle position is offset to dorsiflexion, the net contribution of the plantarflexors increases and the net contribution of the dorsiflexors decreases as expected.

Influence of the stiffness and neutral angle of an AFO on the muscle activation pattern of a healthy test subject.\(^{[16]}\)

\[\text{Note: More important than the material, is how the material is fitted and formed to the patient. Even the best material will be deemed useless if not moulded properly. Milling can provide a good solution to making the material to be stronger yet thinner, improving the overall aesthetics and bulkiness of the prosthesis.}\]

\textit{Why is there a fitting?}

Correcting the positions of the various parts of the foot is a complex undertaking. Because it is difficult to obtain a perfect impression and because there can be day-to-day changes in tone of the foot, orthotists adjust the AFO to accommodate small, but important, differences between the time the impression is taken and the time of application.

\[\text{To cost) the patient may outgrow it and it may become uncomfortable or dangerous to wear, due to lack of support or high stress on the limb.}\]

\textit{comfort}

\textit{Comfort whilst may not be considered a necessity, may be a good indicator of how well the orthosis fits and later problems of the orthosis. If it is very hot, it may be an indicator of a later problem such as excessive sweating. Another example is skin lesions; if the patient feels rubbing it could lead to open wounds or rashes and lead to infections. Figure (G).}\n
\[\text{Fig}^{[F]}\]

\[\text{This can be analysed using an FEA model. Which can also look at strength of orthosis and breakage points. Figure (g).}\]

AFO modelling physical and virtual.\(^{[G]}\)

\textbf{Biomechanics Of Foot Drop In Relation to Designing an AFO}

\[\text{Figure 2: Rotation Axes for Foot and Ankle}\]
Effectiveness Of Ankle Foot Orthoses

- In a study that looks at effect of AFO on Gait Parameters of Hemiplegic (half-paralysed) subjects, the average age of the 40 subjects was 62.5 ± 13.3 years. When using the AFO both the acute (0.7 ± 0.4 months post CVA) and chronic (50.7 ± 37.5 months post CVA) groups significantly increased walking velocity, cadence, stride length and bilateral step length. Bilateral step length parameters improved significantly and affected side step length improved as well. However, there was no significant improvement in step length symmetry. The chronic group walked with a significantly faster cadence than the acute group in both with and without AFO. Other parameters were not significantly different at the alpha equal 0.05 level between the acute and chronic group.

As well as this, other studies have shown that:

- Side to side ankle stability increases (with solid or pre articulated AFOS)
- Walking speed increases
- Balance increases
- Rate of fall decreases
- Energy expenditure while walking decreases
- Knee stability increases

A video on How an Ankle Orthosis Affects Gait.
https://www.youtube.com/watch?v=coHzvRCqyqk

The Electrical Approach - Functional Electrical Stimulation

Nerves

The second most common cause of foot drop, after radiculopathy, is a peroneal neuropathy (degenerative disorder linked to diabetes that affects the nervous system). Peroneal neuropathy, caused by compression at the fibular head, is the most frequently diagnosed compressive neuropathy in the lower extremity, of which foot drop is its most notable symptom.[6][7]

Foot drop can also be caused by strokes, cerebral palsy or multiple sclerosis which all affect the brain or spinal cord. Patients who have suffered from one of the disorders with intact peripheral nerves are the most appropriate candidates for functional electrical stimulation (FES). This technique invokes active gait alteration and correction which can be tailored to the individual patient. Patients with pacemakers, uncontrolled epilepsy, have broken skin or are pregnant are not candidates for FES.

An electrical stimulation device involves attaching two electrodes on the skin of the patient, one close to the nerve involved and the other over the relevant muscle. These electrodes are connected to a battery-operated stimulator which is kept in a pocket or attached to a belt. This stimulator produces electrical impulses that mimic those propagated along nerve cells, to contract the necessary muscles. A sensor is worn in the shoe which triggers the stimulator; it’s activated when the heel leaves the ground as the person walks and stops when the foot again contacts the ground. Electrodes can be implanted under the skin for long-term use. To implant the electrodes, the patient has to be placed under general anaesthesia.

Research

One research group who monitored the use of FES found that even when the electrical stimulator is switched off, walking performance of a foot-drop patient can be improved by FES. Their trial involved patients with progressive (e.g. multiple sclerosis) and non-progressive (e.g. stroke) disorders who used a foot-drop stimulator for 3-12 months. Their electrophysiological
variables (flow of ions in biological tissues) and walking performance were measured before and after the FES device was introduced and worn for a certain amount of time. They measured parameters called motor-evoked potential (MEP) and maximum voluntary contraction (MVC - a measure of strength) from the tibialis anterior muscle using a surface electromyogram. MEP is “the electrical response evoked in a muscle or motor nerve by electrical or magnetic stimulation.”

They observed that MEP and MVC increased dramatically by using the FES device in both groups. The stimulator increased the walking speed by 24% for non-progressive disorders, with the speed increasing by 7% in the progressive disorder patients. These changes “suggest that regular use of a foot-drop stimulator strengthens activation of motor cortical areas and their residual descending connections, which may explain the therapeutic effect on walking speed.”

A research group in Canada (Dai, R et al) produced a paper called “Application of tilt sensors in functional electrical stimulation” in June 1996. They studied various tilt sensors to observe their performance in measuring the angular displacement of regions of the leg during the walking gait. They stimulated the peroneal nerve and altered the stimulator thresholds to suit individual patients, along with the various periods of stimulation. Their device provides many important aspects and advantages over the traditional AFO or any stimulators which are controlled by foot switches. Their initial trials showed “substantial gait improvement” for some of the patients and the majority of patients appreciated the “good cosmesis and ease of using the device with a tilt sensor.”

**WalkAide**

The **WalkAide** team has taken the FES technology and applied it to a revolutionary medical device that people living with foot drop can wear to allow them to improve their quality of life, even allowing them to travel long distances with less fatigue when walking quickly. The WalkAide is a class II device cleared by the FDA which can be worn by patients with upper motor neuron conditions or injuries that include MS, stroke and cerebral palsy. It does not, however, work with patients who have lower motor neuron/peripheral nerve damage.

The device allows the wearer to lift their foot at the appropriate time to restore nerve-to-muscle signals. The WalkAide provides the user with a smoother, safer movement that looks and feels more natural. Functionality, mobility and overall independence of the wearer can be significantly increased by improving their walking ability.

The WalkAide uses “advanced tilt sensor technology to analyse the movement” of the patient’s leg. This sensor can adjust the stimulation timing of each and every step the user takes,
continuously altering to provide a safer and more comfortable stepping motion. The device is battery operated (AA) and contains two electrodes directly applied to the skin of the leg which prevents surgery being involved. A discrete cuff holds the device in place and can be hidden under clothing.

WalkAide provides many advantages that typical foot drop treatments may not. They include "easy one-handed operation and application", any or no shoe can be worn and it has minimal contact with the body making the device more comfortable which reduces irritation through perspiration. The device is a "small, self-contained unit" and has many additional health benefits such as improved circulation, increased range of motion at joints and reduced atrophy.

The user can exercise their muscles while resting using the pre-programmed exercise mode. Each device is tailored to each individual by a clinician using the 'WalkAnalyst' software so they can achieve optimal efficiency and success with their specific walking pattern.[10]

Saebo

Saebo is a "leading global provider of affordable evidenced-based therapy solutions for individuals suffering from impaired mobility and function."[11]

Saebo have created a biofeedback electrical stimulation system called The Saebo MyoTrac Infiniti. Biofeedback or electromyography (EMG) is particularly helpful when muscle contraction is very small. EMG feedback "provides a real time state of muscle activity during movement." The patients are able to be more aware of their physical capabilities which can give them more motivation and better functional outcomes.

The MyoTrac Infiniti stimulates the necessary muscles to improve gait which are determined by the patient's own EMG signal. This non-invasive technique can allow patients to "learn new tasks or modify existing motor patterns." For the use of foot drop suffers, the biofeedback system monitors calf muscle EMG signals and stimulates the dorsiflexors. Once plantarflexion (pointing of the toes) ends at the start of the swing phase in the gait cycle, the device stimulates the dorsiflexor muscles to contract.

EMG-triggered stimulation involves a prescribed threshold that the patient must reach during muscle activation. If the threshold is exceeded, stimulation enhances muscle contraction beyond the patient's ability. When a person has a stroke, brain tissue is damaged and the healthy surrounding tissue will take over the functions that the damaged area was in control of. Through stimulation, the brain can reorganise and form connections between the neurones that are still intact, achieving neuroplasticity.[12]

FES vs AFO

AFOs need special shoes to fit and are generally bulky. FES is more light and can be better concealed and can be worn with almost any type of shoe. FES involves active muscle contraction whereas the AFO technique is passive to correct the gait of a patient. The FES strategy has the advantage of being able to reconstruct the neural pathway which the use of an AFO does not and the act of stimulating the muscles prevents muscle wastage. Although, FES does not work for people who have problems with the nerves in their feet. The AFO can be seen as cosmetically unappealing and holds the foot at 90 degrees, which is unnatural for the gait cycle and can cause difficulties with everyday tasks that require plantarflexion. Also the unbalanced bulkiness and weight AFO provides to one foot, can cause an unsymmetrical gait. FES provides a more normal gait pattern and can be undetectable to a stranger. FES is much more expensive than the purchase of an AFO.

References

1. Medscape Foot Drop Information
2. Current Concepts in Diagnosing and Treating Drop Foot
3. Anterior Ramus Of Spinal Nerve
4. NICE - FES for Drop Foot of central neurological origin
5. Foot Drop Treatments
6. NHS - Foot Drop Information
7. Neuralink - FES for Dropped Foot
10. WalkAide website
11. Saebo website
12. Saebo - Cortical Plasticity
13. Long-Term Follow-up to a Randomized Controlled Trial Comparing Peroneal Nerve Functional Electrical Stimulation to an Ankle Foot Orthosis for Patients With Chronic Stroke
14. Foot Drop - Gait Cycle
15. Scheck & Siress - AFO (Ankle Foot Orthosis) - Plastic
17. MEP definition

Figures

B. http://hubpages.com/health/Living-with-Foot-Drop
C. https://en.wikipedia.org/wiki/Plantar_fasciitis
E. http://usorthotics.com/shop/afo/model-bsw-swedish-afo/
F. http://usorthotics.com/shop/afo/model-bsw-swedish-afo/
G. http://www.tcnj.edu/~afo/index.html


http://dx.doi.org/10.1682/JRRD.2014.02.0046

N. http://www.saebo.com/saebo-myotrac-infiniti/
O. http://www.walkaide.com/patients/Pages/default.aspx

Further Reading of Studies looking at effect of AFO on gait parameters


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