Foot drop: What are the major causes and do patients get optimal treatment?

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Foot drop is a medical condition describing a pathological gait in which the foot keeps dangling down during swing and when the foot might slap on the ground during heel strike. There are several causes that can lead to foot drop and some of these will be described in this article. Furthermore possible therapies are being addressed to see if patients get optimal treatment and in what areas it can be improved. The focus will be mainly on the surgery performed when the peroneal nerve is damaged and possible external devices that are intended to take over the nerve function, like drop foot stimulators or to take over the nerve and muscle function looking at possible ankle foot orthosis.

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Abstract

Foot drop is a medical condition describing a pathological gait in which the foot keeps dangling down during swing and when the foot might slap on the ground during heel strike. There are several causes that can lead to foot drop and some of these will be described in this article. Furthermore possible therapies are being addressed to see if patients get optimal treatment and in what areas it can be improved. The focus will be mainly on the surgery performed when the peroneal nerve is damaged and possible external devices that are intended to take over the nerve function, like drop foot stimulators or to take over the nerve and muscle function looking at possible ankle foot orthosis.

Introduction

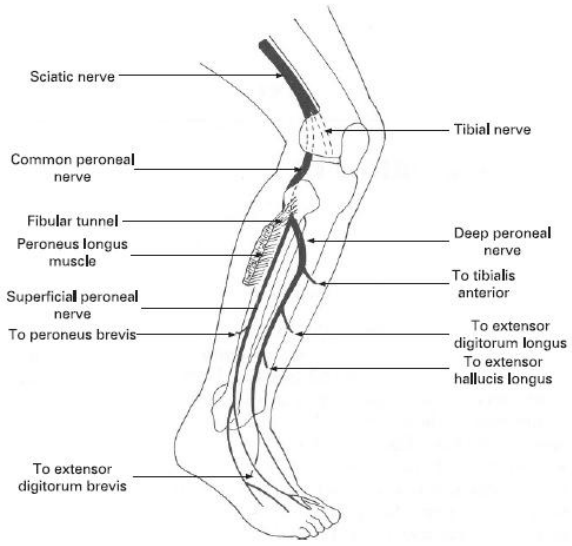
Dropfoot is generally caused by weakness of only the dorsiflexor muscles in the lower leg. Weakness of these muscles can lead to unwanted situations during locomotion. Limited or no function of the dorsiflexor muscles will lead to a foot that kees hanging down during swing. The specific gait pattern will be discussed in the next part. In the less severe cases the patient will experience a slap foot, so any time this foot makes initial contact (IC) the foot 'slaps' on the ground. When the situation is more severe, the foot can't be lifted enough and the toe touches the ground first during IC. When patients walk on uneven terrain with this condition it can lead to stumbling over.

The causes of foot drop are diverse. It can range from muscle pathy to different neuropathologies. This article will focus on different major causes of foot drop and possible treatments for those different pathologies. The most important cause mentioned is direct trauma. Finally the article will answer the questions what possible treatments can be used for different patient groups, if patients get optimal treatment. Finally some ideas of possible future research will be mentioned. Everything will be focussed on patients only suffering from foot drop, which means that the plantar flexor muscles are still intact.

Anatomy

It is important to understand the lower leg anatomy and how it functions before pathologies will be discussed. An important joint for propulsion and support is the ankle joint. The anatomy will also be limited to this joint, because this movement is affected with drop foot. Important motion directions of the ankle are dorsiflexion, in which the foot moves upwards and plantar flexion when the foot moves downwards. Dorsiflexion movement is generated by the dorsiflexor muscles, which are the m. tibialis anterior, the m. extensor digitorum longus and the m. extensor hallucis longus. These muscles are placed at the anterior side of the lower leg. The plantar flexion is controlled by the plantar flexor muscles, which are the m. soleus and the m. gastrocnemicus are the most important muscles. This muscle group is situated at the posterior side of the lower leg(1).

The main dorsiflexor muscle, the m. tibialis anterior, is innervated by the common peroneal nerve (CPN). The CPN is derived from the sciatic



nerve, which originates from the L4-S3 vertebra. The sciatic nerve seperates in the thigh, just above the knee and one of these brances is the CPN. It is important to know that the CPN passes laterally through the popliteal fossa and then winds around the head and neck of the fibula. This area is sensitive to pressure,

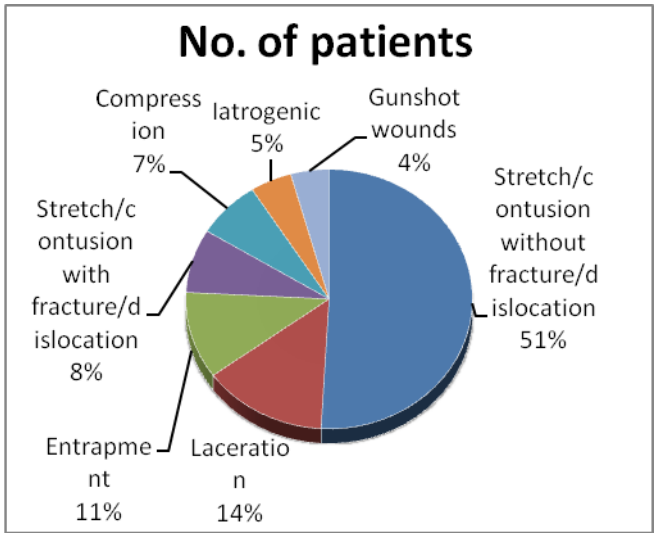
Figure 1: Nerves of the lower leg (3).

because the nerve is situated almost directly between the skin and bone. The nerve then pierces through the m. peroneus longus to reach the anterior compartment where it divides in the superficial and deep peroneal nerve (figure 1)(2,3).

Gait

The gait cycle can be used to determine the ankle involvement during walking. Generally the gait cycle can be divided into two major phases, stance and swing. Stance and swing can be further divided into eight stages. The stance phases are: initial contact, loading response, mid stance, terminal stance and pre swing. The last stage can already be seen as swing and will go on in initial swing, mid swing and terminal swing after which the cycle starts over again (figure 2).

The ankle has different functions during the gait cycle. Important is the function during IC. In this phase the ankle prepares for the loading response and further the ankle needs to preserve progression and provide shock absorption. In the following loading response



Graph 1: Causes of damage to the common peroneal nerve(5).

the dorsiflexor muscles need to decelerate the plantar flexion movement around the ankle. This movement is generated because the force vector is located posterior to the ankle. In drop foot condition the dorsiflexor muscles are weakened and therefore it is impossible to hold the foot. This will lead to a distinct slapping sound when the forefoot slaps to the ground. During mid stance the shank moves forward and the ankle rotates in dorsiflexion position. During terminal stance the heel rises off the ground and locks in position by the m. soleus an m. gastrocnemicus. After this stage the m. gastrocnemicus creates the push off moment and the foot will continue to the swing phase.

This swing phase will clearly show problems for foot drop patients. With a mild weakness of the dorsiflexor muscles the foot will return to the normal position of 90 degrees and only create a slapping sound during the loading response.

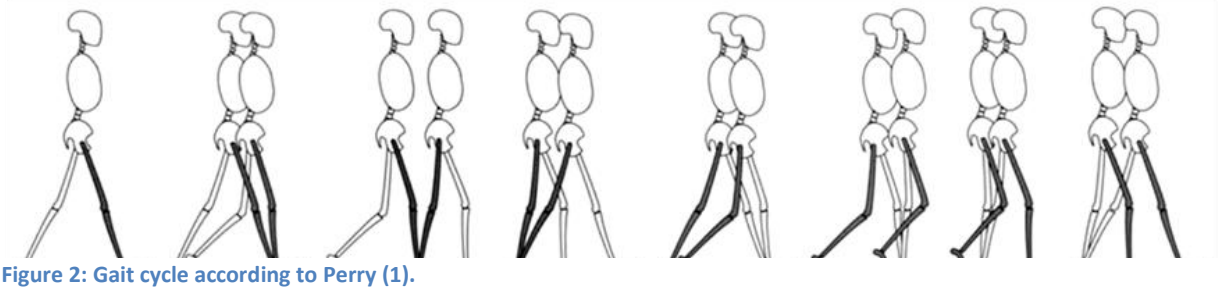


Figure 2: Gait cycle according to Perry (1).

When the weakness of the dorsiflexor muscles is more severe, it will result in a foot hanging down during swing. This elongates the leg and makes walking more difficult(1). This will create a hemiplegic gait pattern in which the toe drag will be overcome with increased flexion of the swing limb hip and knee(4). Toe drag will also increase the risk of falling when walking on uneven terrain.

Causes for foot drop

There is a wide variety of causes that can lead to foot drop. It is already mentioned that pathologies can be related to the muscular system or to the neural system. The most common cause for drop foot is damage to the common peroneal nerve. This damage is often caused by lesions from different origins or compression of the nerve(2,3). According to Kim et al. common peroneal nerve damage due to trauma can be divided in seven different causes, all with different characteristics regarding tissue and nerve damage (graph 1)(5).

Besides neuropathies to the common peroneal nerve, foot drop can also be caused by other (neurological) problems. Some examples are: L5 or, though less commonly, L4 radiculopathy, most often caused by a herniated lumber disk (HLD). Heavy metal (e.g.: lead) poisoning, early course of motor neuron disease, like the Charcot Marie Tooth disease(6) can also lead to foot drop. Cortical lesions or spinal cord injury is also an example(2). And then there are still some rare cases that lead to foot drop like spinal stenosis at the C4-C7 and T11-T12 level or meningiomas that affect the motor cortex in the brain.(7). Other causes can be muscular dystrophy, heavy metal poisoning, e.g. lead toxicity in children may cause foot drop without sensory loss, or the anterior compartment syndrome(2).Due to the wide variety of causes,it can be difficult to find the actual cause.

Surgical treatment

Very common CPN injury is stretching or contusion. This type of injury is often caused during sports- or vehicle accidents. The method of treatment depends on whether the injury is accompanied by bone fractior or dislocation of the knee or not. For the cases without dislocation of the knee or fractures the patients first will be examined for neural function. Initial examination involves EMG testing of the muscles. When functional recovery is not recorded patients will get surgical exploration of the nerves. The nerves will be tested intraoperative for nerve action potentials (NAP). The results of this test will determine how the nerve will and can be treated. In case of positive NAP recordings, which indicate regeneration across the lesion, external neurolysis is performed. Damaged and unwanted tissue is removed to create an optimal environment for the recovering nerve. Nerve grafts are being used to repair the lesion when the NAP test is negative. Autologous donor grafts are taken from the ipsilateral, contralateral or the sural nerves. These nerves are chosen because they are not important for normal functioning of the leg.(8).

About a quarter of the patients with a knee dislocation combined with or with proximal fibular or tibial fractures have CPN damage. During primary treatment, shortly after the injury, the treatment focuses on recovery of the joint and tissue. For dislocations possible reconstructions of the ligaments are made and fractures are set. In a later stadium neural damage is being tested and, if necessary, treated. The neural damage is being treated in the same manner as mentioned before, with external neurolysis or nerve grafts(9). Similar nerve damage (i.e. lesions in continuity) are also seen in patients with iatrogenic injury, lacerations damaging the nerve and gunshot wounds(5).

Other kinds of CPN damage can be due to compression injuries. Those compression injuries are often caused by external pressure on the nerve. The most likely place for compression is around the fibular head where the nerve lays almost immediately on the bone, only protected by the skin. Sleeping or sitting in abnormal positions can already create pressure points. Habitual leg crossing is also an important factor for nerve compression. Other examples of compression can be the use of leg braces with edges just below the knee, plaster casts over the knee or tight bandages(3). Compression injuri is treated following the same procedures as for treating contusion or stretching damage to the nerves.(5).

Finally there are some internal causes to CPN damage. An example is entrapment of the nerve around the head of the fibula or contrapment where the nerve passes through the fibular tunnel. This can often be solved by widening the tunnel and creating a free pass. Tumours and masses can also create neuropathy. Tumours can develop within the nerve tissue, directly damaging the nerve or in tissue surrounding the nerves, which creates compression of the nerve and therefore limited functionality. To find tumours both CT and MRI imaging examinations can be used. When cysts are found on these images they can be removed surgically, often resulting in appropriate functional recovery(3,5,10).

Dorsiflexion function of patients is tested after treatment to decide if treatment was successful. Therefore the dorsiflexion force is measured on a scale from 0 to 5, in which 0 stands for no muscle contraction. A score of 3 (contraction against gravity and some resistance) is considered as successful and the maximum score is 5 (contraction against great resistance). From long term monitoring of patients and evaluating the outcomes of surgery neurolysis shows to be successful in almost 90% of treatments. Nerve grafting is less successful, the longer the graft the lower the chance on a sufficient recovery. The success rate is 40% average(5,9).Ankle foot orthoses

An ankle foot orthosis is an external device that prevents drop foot. An AFO can range from simple, rigid plastic splints to more sophisticated carbon splints or hinged designs. All AFOs are designed with the same intention: make patients mobile again. Important requirements for AFOs are, for example, that foot drop is functionally supported (i.e. provide dorsiflexion motion), the AFO is comfortable to wear(11). Other requirements involve a certain degree of plantar and dorsiflexion freedom and

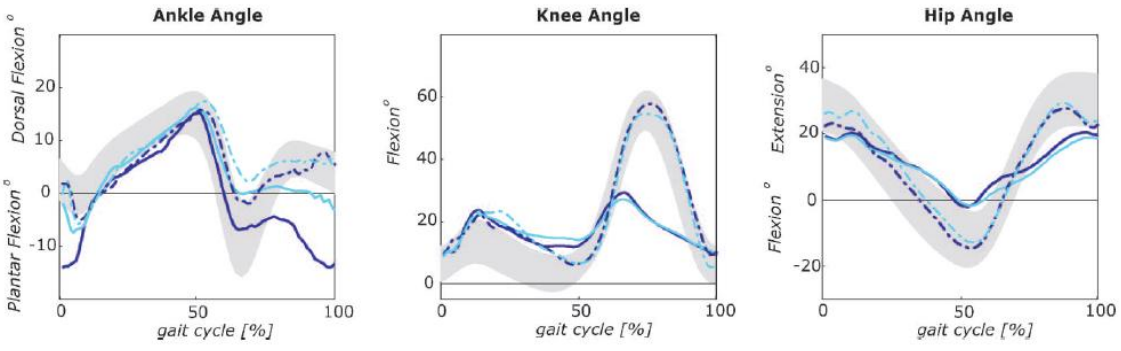


Figure 3: Walking without AFO benefit group: dark solid line; walking with AFO benefit group: light solid line; walking without AFO non-benefit group: dark dashed line; walking with AFO non-benefit group: light dashed line. Shading represents normal gait(14).

providing a resistive moment against plantar flexion(12). Those examples come from more recent developed AFOs. Older AFOs are often simple plastic splints, made out of polyethylene or polypropylene and moulded around a plaster cast of the lower leg. The basic function of those plastic AFOs is to maintain the ankle in a neutral position during swing and to control plantar flexion immediately after initial contact. Which means that the AFO is able to absorb the impact of bodyweight and to support forward propulsion of the body during terminal stance(13).

There are several ways for testing the effectiveness of AFOs. Parameters that can be tested are related to the biomechanics and kinematics of walking. In research performed by Bregman et al.(14), two tipes of anterior leaf spring AFOs are tested. Tested characteristics are the energy expenditure of walking, stiffness of the device and influence of walking speed and kinematics. Only half of the patients seem to benefit from using an AFO when solely looking at energy expenditure and walking speed results. Movement analysis shows why only half of the patients show benefits. The non benefit group show that they are still able to keep their ankle in a neutral postion during swing (figure 3). The AFO therefore only hinders the ankle movement. The non benefit group on the otherhand show a clear plantar flexion angle during swing phase (60-100% of the gait cycle). When these patients use an AFO the ankle will remain in the neutral position during swing.

The conclusion of Bregman et al. is that low stiffness anterior leaf spring AFOs only give a small contribution to the ankle moment compared to carbon AFOs. They also point out that it is important to fit an AFO to the patients needs, to prevent unnecessary prescription of the devices.

Similar research was performed by Danielsson et al.(15), to evaluate the energy expenditure for walking with a custom fitted carbon AFO and walking without the AFO. The test subjects were stroke patients with loss of dorsiflexor function. Just as previously mentioned, the walking speed increased for walking with the AFO and oxygen uptake per walked meter lowered, resulting in a more energy efficient gait when wearing the AFO. Unfortunately no tests for gait pattern and ankle angles is performed to see the mechanical effect of the carbon AFO on walking.

Farmer et al.(4), on the other hand, show contradictory results. A plastic, off the shelf, AFO show a negative effect on walking speed and comfort compared to walking on regular shoes or bandaging support. This outcomes could be discussed, because patients were already biased on some support methods. There was no trial time with new devices and all patients showed sufficient muscle strength for walking, an average grade of 4. The research confirms the findings of Bregman et al.

Splints are not the only possible devices to support foot drop. Hinged AFOs are another example of supportive devices that can be used. There is some variation in those hinged AFOs regarding movement assistance and blocking capabilities. Some patients might need some dorsiflexion assistance. A plantar flexion block is also common in hinged AFOs to limit the movement in this direction. A simple version of a hinged AFO is made from a custom plastic cast with two hinges mounted at the sides. The plastic part functions as a plantar flexion stop. To allow more freedom of movement Yamamato et al. invented a new hinge(12). The hinge is actually a small oil damper that can be fitted inside a custom fabricated AFO. The most important function of this AFO is to prevent rapid plantar flexion of the ankle joint during initial stance. The final device provides a plantar

flexion resistive moment up to 14 Nm at a planter flexion angle of 10 degrees.

Another possible new design for a hinged orthosis is made by Bishop et al. (11)(11)(11). Major design criteria are that the orthosis is comfortable to wear for longer periods and that the orthosis can be used when running. This resulted in a custom fit AFO with plastic hinges. The hinges are able to generate enough moment to lift the foot. The placement of the AFO has changed compared to anterior leaf spring AFOs. The new design is placed around and on top of the foot, leaving the foot bed in direct contact with the shoe.

Functionality of supportive devices is important, though comfort can't be underestimated. It works the same with uncomfortable clothing as uncomfortable AFOs: they will not be worn. Farmer et al.(4), mention in their results that patients experience the leaf spring AFO as the least comfortable. Phillips et al. (6) have also tested user experiences thoroughly using questionnaires for AFO users with Charcot Marie Tooth (CMT) disease. The research focuses on creating insight into the benefits, disadvantages and important characteristics of the AFO. Another focus point was to discover possible barriers for using those supporting devices.

The research that is performed makes a clear distinction between non-/ inexperienced users, users and orthotists. This is done to get specific data for the different user groups. The questionnaires are adapted to the specific user group about experiences with the device, disadvantages, barriers for using them and important characteristics about using the AFO. The most important benefits that are mentioned for the different groups are related to the increase of mobility. The disadvantages of AFO use show to be different for female and male users. For the female users the aesthetics of the AFO is an important disadvantage, where the male users mention discomfort because of different sores and restricted movements in tight spaces. Prejudices of the non user group appear to be more regarding functionality, e.g. restriction of movement, limit flexibility and the bulky, heavy look. Overall support and comfort are the most important characteristics for an AFO.

Functional electric stimulation

An alternative device to an AFO can be a functional electric stimulator (FES). The FES is designed to take over the innervating function of the damaged nerves. External stimulation should lead to innervations of the dorsiflexor muscles. A review by Lyons et al. (16) shows the history of electrical stimulation devices, which already started in 1961. The development of these drop foot stimulator (DFS), or FES devices, as they are called, can be divided in 4 types: hard-wired single-channel surface DFS, hard-wired multichannel surface DFS, hard-wired single-channel implanted DFS and microprocessor-based surface and implanted DFS.

The first stage in the evolution of a hard wired DFS is a simple configuration of a switch in the sole of the shoe. The switch detects pressure of the foot on the sole to detect the stag of the gait cycle. This resulted in regulation of electrical muscle stimulation.In the early devices this pulse was continuous and later on it evolved in short pulses with a certain frequency range. This improves the comfort of electrical muscle stimulation. New incorporated features are the use of both manual and foot triggering as well as ideas of using the EMG signal of other muscle groups to trigger stimulation. The development of the hardwired stimulator evolved to a design with several clinically useful features. It was fitted with a switch that could both be worn on the affected leg or the healthy leg, to ensure that the pulse is triggered by a distinct signal. It was also fitted

with potentiometers that resulted in real time adjustments of the rates of stimulation.

Multichannel surface DFS have the advantage that different muscles can be triggered individually. The sequence of triggering the muscles can also be adjusted optimally. A large disadvantage is that more electrodes need to be fitted at the skin of the patient in exact locations. When the two electrodes for a single channel stimulating device already cause irritation, than several more electrodes, necessary for the multi channel system, would b really time consuming. The wires might as well negatively influence the freedom of movement during walking.

Another possibility is to implant both systems, meaning that the electrodes for stimulation are being inserted to the body and attached to the nerves to trigger muscle activity. In early designs only the electrodes are implanted. Radiofrequency signals are then used to trigger the electrodes. Later on, with the use of a microprocessor, it becomes easier to design smaller devices. Controlling the (multichannel) stimulators also gets more sophisticated. This results in wearable devices that transmit the electrical signals through the skin.

Remarks that are found for treatment with stimulatory devices are the limited number of patients that are suitable to use surface stimulation. Only a small number of patients will continue using the DFS on the long term. And one of the most important factors is that patients have to tolerate the transcutaneous shocks that create sensation at the skin. Further, the device should also be user friendly, which is difficult with many devices that require every day positioning of the leads. Difficulties also show up in operating the device and possible allergies to the electrodes on the skin.

Alternatives to autologous grafts

It might be interesting to look further then donor parts or external devices to find other solutions to overcome foot drop. The initial goal of inserting nerve grafts is to overcome the lesion in the damaged (peroneal) nerves. Alternatives to grafts can probably be found in regenerative medicine. Stem cell research, as well as understanding cell growth is important in this wield. Therefore new ideas and methods about regeneration and growth of nerves can be found.

Small neuronal are generally overcome with mobilization of the nerve and joint positioning. In the cases that this is not possible, bridging material is required. Instead of using autologous nerve grafts, as mentioned before, this bridging material could also be a tube, or conduit, to guide the nerve when growing back. The use of neural tubes has the advantage that the nerve is not tightened at the stitching site. The nerve is put loose inside the tube and is attached to the tube with one or 2 stitches. The nerve endings are stitched together directly for autologous grafts, resulting in a tensional area. This tensioning negatively influences regeneration. Another advantage is that nerves can be resected to the healthy parts and there is no graft necessary from anywhere else in the body. The ideal conduits would cause little or no inflammation and if the tubes are made of biodegradable material secondary surgery for possible compression is not necessary. When nerve conduits are being used in restoring nerve gaps, both nerve ends are being attached for 2 mm in the tube by a suture. Therefore the tube should be a little larger than the nerves. Results so far are that about 75% of the patients that are treated with conduits recovered, which is similar to the success rates of autologous grafts for small neural lesions (up to 3 cm)(17).

So far only small nerve gaps are being closed with nerve conduits. Research continues to

conduit properties that allow nerve generation over longer gaps. Different techniques are being used to achieve this, both structural as with additives. Examples are filling of the tubes with collagen and laminin containing gels, adding growth factors or Schwann cells to the tube. Modifications of the micro-architecture (for example: filament structure, multichannel structures, spongy structure) is also being studied. To close the longer gaps in peroneal nerve gaps the physical aspect of the conduits is also becoming important. The tube diameter should be large enough to be able to fit around the nerves and the tube should be strong enough to resist external forces and prevent collapsion. All necessary to keep the nerve growing(18).

De Ruiter et al. (18) mention different requirements for nerve conduits to be designed in the future. A few are mentioned already in the previous paragraph. Important for all living cells is a sufficient oxygen and energy supply. This can be created by making the outer material of the conduits permeable, for example to fibre spin the material used for the conduit. Another possibility is to add crystalline structures like sugar or salt to the mould of the graft. These substances can be solved in water afterwards, resulting in an open mesh tube wall structure. Materials that can be used are preferably biodegradable, like polymers from lactic and glycolic acid or caprolactone. This will allow the conduit to degenerate after time and prevent compression of the nerves by the conduit. A possible danger in using biodegradable materials is that they might swell during the hydrolysis, which can result in unwanted compression on the nerves. Furthermore the right mix of rigidity and flexibility should be found to prevent the conduit from collapsing and if it happens, the conduit shoul d be flexible enough to get back in the original shape. Furthermore it is important to prevent easy tearing or breaking from occuring.

Nerve regeneration can be induced by filling up the nerve conduits with Schwann cells or to add different growth factors. Those growth factors may enhance regeneration mechanisms like promotion of axonal outgrowth and neural survival. Matsumoto et al.(19) report about a nerve conduit that successfully guided nerves to regenerate over an eight cm wide gap in the peroneal nerve of dogs. The conduit they used was designed out of polyglycolic acid and collagen. The internal space was filled with laminin coated collagen fibres. After a year of follow up 2 implanted and one control animal showed signs of infection. The infection was caused by the sutures. The animals with the tube implantation were able to walk normally again without carrying load after this year. The control group without implantation was still limping with the operated leg. The implantation group also showed conductivity of electrical signals. Further development of this technique might result in future conduits that can be used to fill larger nerve gaps.

Other developments are being made in the use of multipotent cells. These cells can be influenced by growth factors and other chemical substances to form, for example, Schwann cells, which are necessary for nerve growth. Research by Dezawa et al. (20) show that it is possible to influence bone marrow stromal cells (MSCs) so that they transform to Schwann cells. These cells prove to be active in regeneration of nerve tissue. In later research done by Shimizu et al. (21) it is tested if human MSCs would act the same. After being treated chemically the cells are suspended in a matrigel that is used to fill the conduits transplanted into rats. Evaluation of nerve tissue through microscopy shows that the human MSCs also change shape and the induction process of human and rat MSCs are similar.

Conclusion and discussion

Foot drop patients do get good treatment for their condition. Like many other diseases it is not always possible to solve the problems completely and therefore alternatives are present. The wide variety of pathologies can make it difficult to find the base of the disease.

For the clear causes that involve direct damage of the nerves surgical treatment should be optimized. The results for neurolysis are already good, with a success of almost 90%(5). Conversely, nerve grafting is nerve grafting is not. Future research should be focussed on how nerve grafting could be made more successful. So far in surgery the damaged nerve is being replaced by a graft and the body should heal it by itself. What are the effects of adding growth factors to the lesion side, or other stimulating chemicals? Another question that can be asked is if nerve tubes are viable to use in peroneal nerve damage. This would result in situations that nerve grafts are not necessary anymore.

Despite the good results with some surgical methods there will remain a number of patients that can't be helped with these methods. An obvious alternative treatment is using an AFO. In spite of the variety in orthoses patients are in general not satisfied with their orthosis. As comes forward in the studies performed by Farmer and Philips the orthosis gives patients a lot of discomfort. The patients experience discomfort regarding to the fit, that the orthosis is causing pressure sores or that the orthosis rubs. Secondary they experience discomfort regarding the freedom of motion and support(4,6). Therefore it is important that development of the orthoses keeps continuing. The focus point should be on comfort to wear and sufficient freedom of movement with preservation of support. Therefore it could be interesting to find a general, but customizable, solution for both parts that might be used together. In important focus point for DFS devices is usability. The devices that can be used without surgery involve wired electrodes that require placement, day in, day out. Improvement of the usability will cause that patients that start using the device and who can withstand the continuous transcutaneous shocks to keep using the device.

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