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Technical note

Analysis of body-device interface forces in the sagittal plane for patients wearing ankle-foot orthoses

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Abstract

An ankle-foot orthosis (AFO) is employed principally to treat musculoskeletal disorders of the ankle and/or subtalar joints although, occasionally, it may be prescribed to provide stance phase control of the knee. In order to function satisfactorily, an AFO must apply appropriate forces to the lower leg in a manner which does not cause local tissue damage or discomfort. Equally the leg will apply forces to the AFO which it must be capable of withstanding without breakage or loss of function. Thus it is useful to know where the body-device interface forces act during walking and to be able to estimate their magnitudes. This is not well understood and has not been satisfactorily documented. This paper explains the force actions between the AFO and the leg, in the sagittal plane, where there is absence of muscle power. Furthermore, it explores the possibility of estimating the magnitudes of these forces. It is found that the forces are greatest when orthotic assistance is needed to compensate for plantar flexor insufficiency in late stance phase. On the other hand, where the AFO is used to support the foot, in the absence of dorsiflexion power in swing phase, the forces are relatively small. Understanding these force levels is relevant to the design of the AFO in terms of choice and use of materials and components.

Introduction

The AFO may be employed to treat musculoskeletal disorders at the ankle and/or subtalar joints. In this analysis, the specific case of insufficiency of the plantar flexors and of the dorsiflexors will be considered and the analysis of forces and moments will be confined to the sagittal plane. The aim is to show that the configuration of body device interface forces can be determined and their magnitudes estimated for key points in the gait cycle (early stance phase, late stance phase and swing phase).

In analysing AFO body-device interface forces, it is important to understand the function of the AFO and this, in turn requires a knowledge of the functional deficit that the AFO is intended to correct. An AFO may be prescribed to treat one or more of a number of different pathological conditions which have been described previously (Sarno and Lehneis, 1971; Rubin and Dixon, 1973; McHugh and Campbell, 1987). It will be helpful to briefly describe the function of an AFO which is prescribed to provide assistance for two of these conditions: dorsiflexor insufficiency and plantar flexor insufficiency.

AFO function in dorsiflexor and plantar flexor insufficiency

Firstly, reduced or absent dorsiflexion power will be considered. The dorsiflexors contribute significantly to ankle joint control in swing phase and early stance phase of walking. During swing phase they exert the small dorsiflexion moment required to support the weight of the foot. In early stance, between heel strike and foot-flat they control the plantar flexion of the foot induced by the ground reaction force acting posterior to the ankle. Weakness of this muscle group can result in rapid plantar flexion in early

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stance phase ending with a characteristic audible foot slap. If the weakness is more marked, there may be insufficient power even to support the foot in swing phase. This leads to the danger of toe contact with the ground (drop-foot, toe-drag) and a consequent tripping hazard. If proprioceptive feedback is intact, the danger can be averted by increased knee and hip flexion during swing phase. Toe clearance could also be achieved by circumduction (swing phase abduction of the non-supporting hip), hip hiking (elevation of the pelvis and non-supporting leg during mid-stance) or vaulting (mid-stance plantar flexion of the supporting foot). In more severe cases it is likely that heel strike will be replaced by flat footed contact or even toe contact. The orthotic requirement is to support the foot in swing phase and resist (but not prevent) plantar flexion in early stance phase.

The second condition to be considered is reduced or absent plantar flexion power. One consequence of severe plantar flexor insufficiency is an inability to oppose the external dorsiflexion moment, induced by the ground reaction acting anterior to the ankle joint, during late stance phase between the instants of mid-stance and toe-off. This reduces stability and eliminates the contribution of ankle motion, at this stage, to preventing excessive lowering of the body centre of gravity. During the mid-stance phase, the role of ankle control by the plantar flexors in stabilising the knee may be replaced by knee extensor activity. An effective AFO can be of great assistance in preventing the unwanted dorsiflexion in late stance. Weakness of the plantar flexors will also result in the absence or impairment of the active plantar flexion which contributes significantly to the forward propulsion of the body during the normal push-off. An AFO is less able to provide this function but some compensation by means of increased hip extensor activity is possible.

In this analysis, total loss of dorsiflexion and plantar flexion power will be assumed. A common prescription in this instance would be an AFO which would prevent motion at the ankle joint. As a side effect, movements such as subtalar rotations may be suppressed but this is usually considered an acceptable compromise. There are alternative designs of AFO which can provide this type of control. The traditional design consists of a calf band (metal covered by leather) connected by metal bars to a robust shoe. The more modern designs include a plastic foot section which is contained within the shoe but is not attached to it. However, in a functional sense, the shoe is an essential part of the AFO and will be considered as such in this analysis. The analysis presented herein may be selectively applied to cases where there is isolated absence of plantar flexion power (affecting late stance phase) or of dorsiflexion power (affecting early stance phase and swing phase).

Force actions

When analysing the force systems which act on the patient and on the AFO, the gait cycle may be considered in two distinct phases: stance phase and swing phase. Stance phase may be subdivided into early stance and late stance although, as will be seen, the method of analysis for these is essentially the same.

Early stance phase

During stance phase (Fig. 1), the ground reaction force, R, is equal and opposite to the force denoted by B which is a combination of body weight and body inertia force. The ground reaction force exerts a moment about the ankle joint (Fig. 2) equal to $(R * a)$ where a is the perpendicular distance from the ankle joint to the line of action of the force R. The moment about the ankle due to the ground reaction is normally opposed by muscle action. If the muscle force is F_D, and the perpendicular

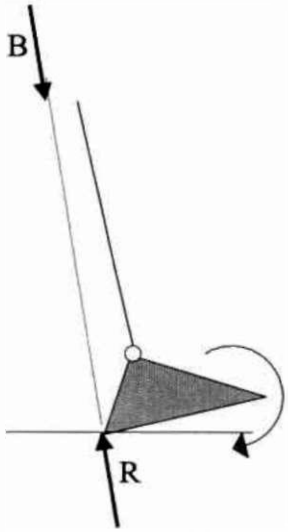

Fig. 1. The ground reaction force *R* is equal and opposite to body weight and inertial effects *B* in stance phase.

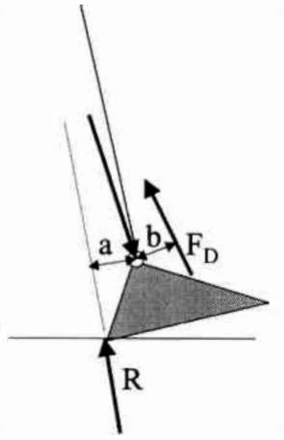

Fig. 2. Forces acting on the foot in early stance phase with normal muscle activity.

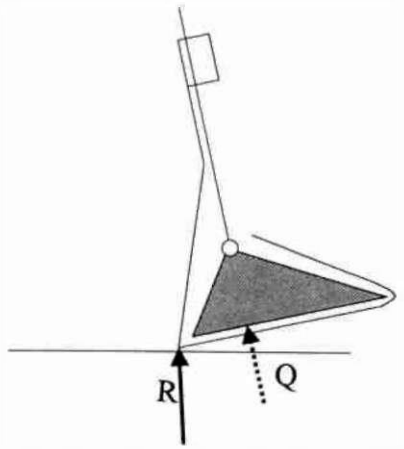

Fig. 3. In the absence of muscle activity, the support force Q applied to the plantar surface of the foot by the AFO will act through the ankle joint.

distance from the ankle to the line of action of the muscle force is b, then the moment exerted by the muscle is $(F_D * b)$. If the foot is stationary, or travelling with constant velocity, the moments acting about the ankle joint are in equilibrium, and thus $(F_D*b) = (R*a)$.

If there is muscular insufficiency such that $(F_D*b) < (R*a)$, this will cause the foot to accelerate and produce the aforementioned audible slap. The weight of the foot makes a small contribution to the plantar flexion moment but in stance phase this may be considered to be negligible, compared with the ground reaction force, and will be ignored in this analysis. If an AFO is used to compensate for dorsiflexor insufficiency, the ground reaction force, in early stance phase, acts directly on the heel of the AFO. The AFO, in turn, exerts a supporting force Q on the foot (Fig. 3). If this force were to act posterior to the ankle joint, the foot would plantar flex involuntarily (since it has no dorsiflexion power) until it reached a position in which there was no plantar flexion moment; that is, the force Q would move forwards until it acted directly through the ankle joint. The precise orientation of the force Q can be determined by further analysis. Since every action has an equal and opposite reaction, a force equal to Q is applied by the foot to the AFO as shown in Figure 4. The AFO would plantar flex were it not for the calf section which experiences the proximal force P. If inertial effects (related to acceleration) are considered to be negligible, then the AFO may be assumed to be in equilibrium. In this case, the forces P, Q and R must satisfy the following criteria:

(i) they must be concurrent (all meet at one point);
(ii) when they are drawn as vectors, head to tail, in any sequence, they must form a closed triangle;
(iii) their components, in any direction, must sum to zero;
(iv) their moments about any point must sum to zero.

The first criterion allows the line of action of force Q to be drawn more precisely since two points through which it must pass (the ankle

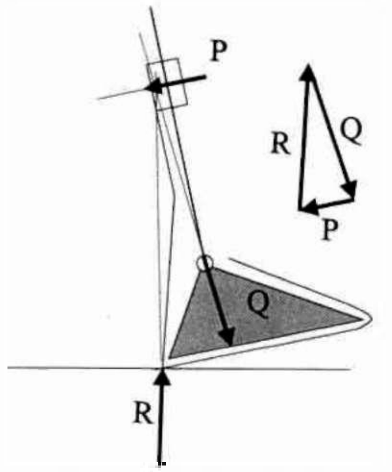

Fig. 4. Forces acting on AFO during early stance phase in the absence of muscle power about the ankle joint.

joint and the intersection of R and P) are known. There are several different ways to proceed with the analysis. The method presented here entails drawing a vector triangle as follows.

(i) Draw a vector representing R (magnitude, line of action and direction known) using an appropriate scale (for example 10mm: 200N).

(ii) From one end of vector R draw a line parallel to force P.

(iii) From the other end of R, draw a line parallel to force Q.

(iv) These lines form a triangle. The lengths of the sides representing P and Q are measured and the forces are calculated using the scale originally used to draw vector R.

Late stance phase

So far, a method for estimating body device interface forces during early stance phase has been described. However the same approach can be used for late stance phase.

The large dorsiflexion moment which occurs between heel-off and toe-off is normally opposed by the gastrocnemius and soleus, which act powerfully though the Achilles tendon (force F_P in Figure 5). Moreover these muscles are capable of producing the active plantar flexion which occurs during this phase. In the absence of plantar flexion power, an orthosis may be prescribed to prevent dorsiflexion. The ground reaction force is borne by the anterior portion of the AFO footplate as seen in Figure 6. It cannot be transferred to the metatarsal heads because, in the absence of plantar flexion power, the foot would passively dorsiflex until the line of action of the force Q between the AFO and the foot passed through the ankle joint. Using the same method as described above, for lack of dorsiflexion power in early stance phase, the body device forces can be estimated as indicated in Figure 7.

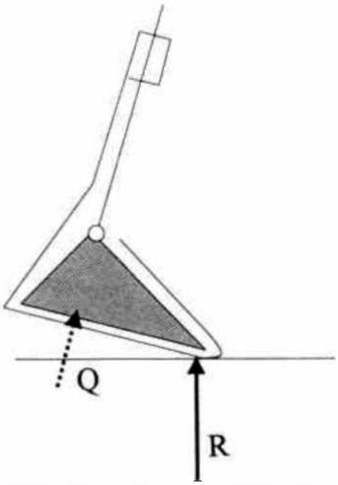

Fig. 6. In the absence of muscle activity, the support force Q applied to the plantar surface of the foot by the AFO will act through the ankle joint.

It is valid to treat each body-device force as a vector acting at a single point in a force analysis of the kind presented here. However, it must be recognised that, in reality, each force would be distributed over an area which should be large

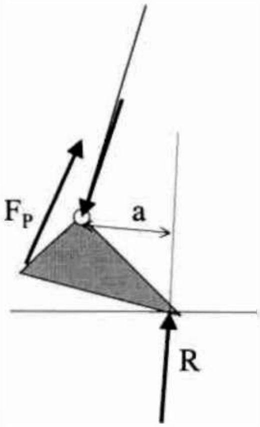

Fig. 5. Forces acting on the foot in the late stance phase.

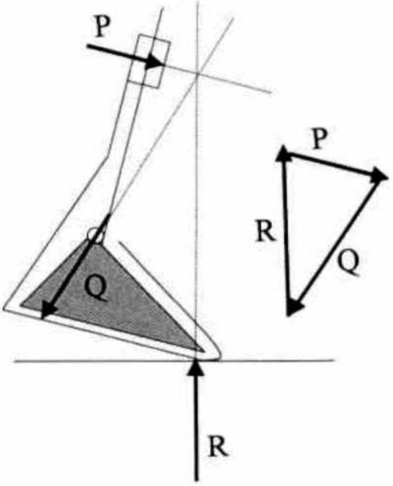

Fig. 7. Forces acting on AFO in late stance phase in the absence of plantar flexion power.

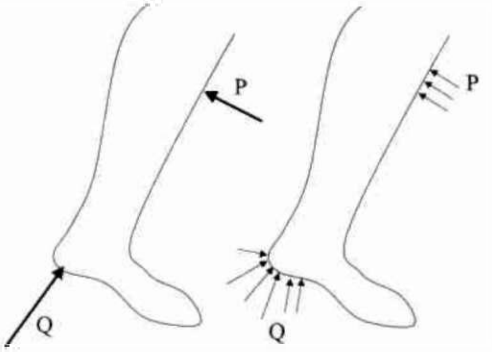

Fig. 8. A force should not act at a single point. It should be distributed over a sufficient area to give an acceptable pressure level.

Fig. 10. Body-device contact points as the foot plantar flexes inside an AFO during swing phase. The AFO is shown larger that the foot for the purpose of illustration.

enough to avoid excessive pressure as, for example, indicated in Figure 8. The precise manner in which each force is distributed is dependent on the way the orthotist shapes the orthosis in the location of that force.

Swing phase

In normal swing phase (Fig. 9), the foot exerts a plantar flexion moment *(W*x)* due to its weight *W* effectively acting through its centre of mass at a distance *x* anterior to the ankle joint. This is counteracted by the dorsiflexors which produce an equal and opposite moment. If dorsiflexion power is lacking, the foot will plantar flex and there will be a risk of tripping. If an AFO is fitted, and the foot attempts to plantar flex contact will occur between the body and the orthosis at the points indicated in Figure 10. The force applied by the AFO to the leg are shown in Figure 11. The foot will apply a downward force *Q* on the AFO in the forefoot region and downward motion of the orthosis will be prevented by a force *S* exerted by the dorsal surface of the foot. As the foot and AFO try to plantar flex, the force *P*, acting in the posterior proximal zone provides a moment *(P*c)* about the ankle which counteracts the plantar flexion moment *(W*x)* due to the weight of the foot. The three forces *P*, *Q* and *S* are in equilibrium and thus can be estimated by means of a vector triangle as shown in Figure 11. To achieve this it is helpful to calculate force *P* from the fact that *(P*c)=(W*x)*. Then the vector *P* can be drawn and lines parallel to *Q* and *S* added at either end of it to form a vector triangle. Again, it must be emphasised that the orthotist determines the precise manner in which these forces are distributed by the shaping of the AFO in the vicinity of each force.

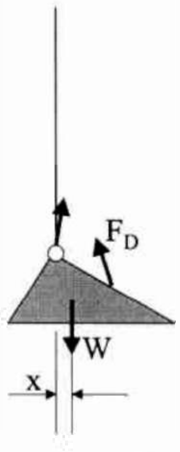

Fig. 9. Forces acting on the foot in normal swing phase.

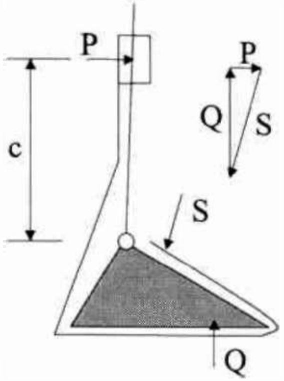

Fig. 11. Force system applied by AFO to body to compensate for dorsiflexor insufficiency in swing phase.

Effect of location of proximal force *P* on its magnitude

It should be noted that, if the aim was to determine only the proximal force *P* in stance or swing phase this could be found relatively easily as shown in the previous paragraph. The force *P* must exert a moment about the ankle joint equal to the external moment M_E due to the ground reaction force in stance phase or the weight of the foot in swing phase. If *P* acts at a distance *c* from the ankle joint, then, summing moments about the ankle gives $(P*c=M_E)$. This shows that, for a given external moment, the further the force *P* is from the ankle, the smaller its magnitude will be.

Magnitudes of ankle moments and design of AFO

As an approximate order of magnitude, the ankle moments, due to the ground reaction, in early and late stance phases are 10Nm and 100Nm respectively. In swing phase the moment, due to the weight of the foot, is less than 1Nm. This is relevant to the design of the AFO. In the case of dorsiflexor insufficiency, the AFO must be able to prevent plantar flexion during swing phase when the moment is 1Nm and permit controlled plantar flexion in early stance phase when the moment is around 10Nm. Where there is an absence of plantar flexion power, the AFO must oppose an ankle moment during push-off, of the order of 100Nm with minimal deformation. Thus an AFO, which compensates for lack of plantar flexion power in late stance phase, must be considerably more rigid than one which is prescribed for dorsiflexor insufficiency in early stance and swing phase. Since the ankle moment to be controlled in late stance, in the case of dorsiflexor insufficiency, is of the order of 100Nm, the correspondingly large proximal orthotic force may present problems at this stage in the gait cycle and requires careful design of the proximal body-device interface.

Effects of spasticity

The foregoing analysis does not take account of the possible presence of inappropriate muscle action related to spasticity. If this occurs during swing phase, due to contraction of the plantar flexors, the resulting force configuration is the same as that shown in Figure 11 for dorsiflexor insufficiency. However, the force magnitudes would be greater depending on the intensity of muscle contraction and it may be noted the calf muscles are clearly capable of producing ankle moments of the order of 100Nm in late stance phase. Thus, if they were to produce a comparable moment in swing phase, it is possible that the body-device force levels could be as much as two orders of magnitude greater than those experienced in the case of absence of muscle power. In reality, the force levels would depend on the severity of the spasticity and should be reflected in the rigidity of the prescribed AFO. During early stance phase the situation would differ from that described above for lack of muscle power. The force *Q* would no longer act through the ankle joint, but would be displaced anteriorly such that its moment about the ankle balanced that due to the force through the Achilles tendon. The proximal force *P*, acting during early stance phase, would be greater than that estimated for the case of absence of muscle power. This is because it must provide the additional ankle moment required to oppose the plantar flexion moment caused by spasticity.

Conclusions

Where an AFO is prescribed to compensate for dorsiflexor and/or plantar flexor insufficiency, the configuration of the body-device interface forces can be determined for any specified point in the gait cycle.

It is possible to estimate the body-device interface forces acting throughout the gait cycle for a person wearing an AFO to compensate for muscular insufficiency, if the configuration of the orthosis and the ground reaction force are known. These body-device interface forces are found to be greatest in late stance phase and least in swing phase.

The distribution of each force cannot be predicted theoretically without precise knowledge of the geometry and mechanical properties of the body-device interface. Each force may be distributed over an area or split into two or more equivalent components which may themselves be distributed in their respective locations.

The ankle joint moments to be controlled by an AFO vary greatly throughout the gait cycle and it is important to identify clearly those periods during the gait cycle orthotic assistance is required before deciding on the structure of the AFO.

The presence of spasticity can increase force levels by an amount which depends on its severity.

The magnitude of the proximal orthotic force is inversely proportional to its distance from the ankle joint and proportional to the magnitude of the ankle moment which it is required to control.

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