A new structural concept in moulded fixed ankle foot orthoses and comparison of the bending stiffness of four constructions

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Abstract

There are many reasons why a rigid ankle foot orthosis (AFO) may be prescribed. In some cases it is desirable that the rigidity is sufficient to maintain a constant ankle position throughout the gait cycle. There is a need to determine a design of cosmetic, lightweight AFO that provides the necessary stiffness whilst being acceptable to the patient, encouraging continued wear with the resultant benefits.

This paper describes an investigation of AFO resistance to dorsiflexion, comparing the stiffness of an AFO with forward trim lines, two designs of reinforced AFOs and an AFO with forward trim lines and an external ankle strap. One reinforced AFO had corrugations moulded in the polypropylene around the ankle, the other had carbon fibre inserts attached to the inside of the polypropylene.

The emphasis was on testing the mechanical stiffness of the four AFO designs: the test procedure did not mimic the patterns of AFO loading during gait. Each design was tested in the same manner by the same examiner.

The AFO with forward trimlines and an ankle strap displayed similar stiffness to the carbon fibre reinforced AFO and both were stiffer than the other two designs.

Introduction

A rigid ankle foot orthosis can be prescribed for a number of conditions and has been claimed to provide several functions, including: keeping the ankle in a neutral position, providing mediolateral stability, control of plantarflexion after heel contact and aid of propulsion in terminal stance (Lehmann, 1979; Sumiya et al., 1996). These attributes are particularly due to the resistance of the AFO to flexion about the anatomical ankle joint. In order for the AFO to perform as described this stiffness must be maintained.

The range of ankle motion during the normal gait cycle is on average, from 7° of dorsiflexion to 20° of plantarflexion accompanied by moments about the ankle axis up to 1.58 Nm per kg of body mass (Winter, 1990), equating to a moment of 110 Nm for a 70kg adult (Lehmann, 1979).

During excessive dorsiflexion loading an insufficiently rigid AFO may "frogmouth" (Lehmann et al., 1992; Clark and Lunsford 1978), when the plastic anterior to the ankle, both medially and laterally, bulges outwards allowing the AFO to dorsiflex. Under such circumstances the AFO can not be fulfilling its prescriptive requirements. Various means of increasing stiffness have been proposed but with little indication of the level of improvement (Fillauer, 1981; Clark and Lunsford 1978). This paper seeks to compare different methods of stiffening incorporated into moulded plastic AFOs and introduces a new stiffening technique using a strap as a structural element, as opposed to an orthotic reaction element as discussed by Stallard et al. (1986). The strap is a tension member acting transversely across the front of the ankle joint to resist frogmouthing.

The work was undertaken to look at the comparative resistance to dorsiflexion of four designs of AFO. The differences in design were
limited, as far as possible, to the methods of stiffening, although it is recognised that factors other than the design around the ankle may affect the stiffness of the AFO.

**Method**

Four (4) AFOs, (Fig. 1) were produced from a single sheet of 4mm thick co-polymer polypropylene from the same cast of an ankle in a neutral position, i.e. 90°. These were an AFO with forward trim lines, an AFO with forward trimlines and a structural strap, an AFO with corrugations made over a former placed around the malleoli on the cast and an AFO with ‘L’ shaped carbon fibre inserts moulded to the inside of the AFO around the malleoli. The structural strap was manufactured from 50mm wide Velcro closing the ankle joint opening in the orthosis. The strap was a full loop of material passing behind the heel thus avoiding the need for rivets which might have a secondary impact on the bending stiffness being investigated. A materials testing machine* was used with the software set to stop the machine if the load exceeded 950N. The AFOs were mounted in the test machine as shown in Figure 2. The fittings had 3 degrees of rotational freedom: full rotation was available in the plane of flexion and approximately ±20° in the others. The mounting jigs were attached to the AFOs with 8mm bolts in similar positions in all cases. A 6mm thick steel plate was secured with 3 bolts to support the sole of the AFO, the central bolt being used to mount the AFO to the lower moving crosshead of the testing machine.

The loading rates demonstrated in normal gait are much greater than the testing machine was capable of achieving, however, in preliminary tests it was determined that the difference in reaction of the AFO to different loading rates applied by the testing machine was negligible, confirming published data (Yamamoto *et al.*, 1993). The loading pattern for the AFO became more consistent after four initial tests.

The test protocol was established as:
- four initial loading cycles;
- six further loading cycles to gather data.
Each loading cycle met the following criteria:
- compression rate of 200mm/min (3.33mm s⁻¹), equivalent to 2.3°s⁻¹ dorsiflexion;
- crosshead travel limited to 20mm, equivalent to 14° of dorsiflexion, or until a maximum load of 950N was applied;
- the load and crosshead travel were recorded with a sample rate of 18.21 samples per second.

After each loading, the crosshairs were manually driven back to the zero position, the AFO was detached and allowed to relax for 15 minutes.

* Instron 1185 with series IX version 5 controller and 1kN load cell
No structural alterations were made to the AFOs during the set of tests, except in the case of the AFO with a strap. The adhesive properties of the Velcro reduced with each loading, so the strap (the loop side of the Velcro) was replaced for each test.

The tests were performed by the same operator over 2 days. The machine was calibrated prior to testing each different AFO and adjusted to zero load before reconnecting the AFO for each cycle. Temperatures were not controlled during the tests, but no marked changes were noted by the observers.

The data was saved as an ASCII file and imported into Microsoft Excel for analysis.

Results

The displacement data were transformed into an angle of dorsiflexion for a given moment using the dimensions shown in Figure 3 and the following equations, where:

\[ U = \text{ankle axis to upper fixation point} \] (fixed = 290mm)

\[ L = \text{ankle axis to lower fixation point} \] (fixed = 141mm)

\[ D(t) = \text{relative displacement of fixation points at time } t \]

\[ D_0 = 402.6\text{mm} \]

\[ \theta(t) = \text{angle between } L \text{ and } U \text{ at time } t \]

\[ \theta_0 = 135^\circ \]

\[ F = \text{force recorded by the test machine} \]

\[ CR = \text{Compression rate (mm s}^{-1}) \]

The separation distance of the jigs is found from:

\[ D(t) = D_0 - CRt \quad [1] \]

Zero dorsiflexion is here defined to occur when the plantar surface of the foot is perpendicular to the leg, thus the dorsiflexion angle, \( \alpha \), is given by:

\[ \alpha = \theta_0 - \theta(t) = 135 - (t) \quad [2] \]

Where:

\[ \theta(t) = \cos^{-1} \left( \frac{U^2 + L^2 - D(t)^2}{2UL} \right) \quad [3] \]

The moment arm, \( A \), is the perpendicular distance between the line of action of the force, i.e. \( D \), and the ankle axis and is given by:

\[ A = \frac{UL\sin\theta(t)}{D(t)} \quad [4] \]

Thus the moment, \( M \), about the ankle axis is:

\[ M = AF \quad [5] \]

The mean and standard deviation of applied moment for a given dorsiflexion angle were calculated for the six cycles recorded for each design. The mean and mean \( \pm \) one standard deviation for the forward trimline AFO are shown in Figure 4.

Table 1. Comparison of applied moment and dorsiflexion angle for published data and tested AFOs.

<table>
<thead>
<tr>
<th>AFO</th>
<th>Dorsiflexion angle (°)</th>
<th>Applied moment (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yamamoto et al 1993</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>Sumiya et al 1996</td>
<td>15</td>
<td>27.5</td>
</tr>
<tr>
<td>Forward trimline</td>
<td>13</td>
<td>40</td>
</tr>
<tr>
<td>Ridge</td>
<td>13</td>
<td>55</td>
</tr>
<tr>
<td>Carbon fibre inserts</td>
<td>13</td>
<td>62</td>
</tr>
<tr>
<td>Forward trimline with strap</td>
<td>13</td>
<td>65</td>
</tr>
</tbody>
</table>

Fig. 4. Graph of bending moment vs deflection angle for the forward trim line AFO showing mean and mean \( \pm 1 \) standard deviation.

t = time from start of acquisition (s)

D(t) = relative displacement of fixation points at time t

D_0 = 402.6mm

\( \theta(t) \) = angle between L and U at time t

\( \theta_0 = 135^\circ \)

F = force recorded by the test machine

CR = Compression rate (mm s\(^{-1}\)).
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Fig. 5. Mean values of bending moment and angular deflection for the 4 AFO designs.

demonstrating good repeatability, typical of all results. A comparison of the mean data for each of the 4 style of AFO are shown in Figure 5: lines denoting mean ± one standard deviation have been omitted for clarity.

This graph demonstrates that all 3 strengthened designs outperform the plain AFO with the carbon reinforced and the forward trimline with structural strap designs being the most resistant to dorsiflexion throughout the range of applied moment. The carbon reinforced AFO demonstrated higher stiffness at low loads but then started to “yield” and was unable to sustain the higher moment carried by the design incorporating a structural strap. There is a paucity of comparable published data, but it can be seen that the values for resultant dorsiflexion from an applied moment in this study exceed those reported for posterior type AFOs (Yamamoto et al., 1993; Sumiya et al., 1996), as would be expected (Table 1).

The claimed errors for the machine are the speed of the moving head, which is correct to 0.1% with a resolution of 0.2μm giving a maximum error of 0.02mm. The reading of load is ±0.5%, thus for the loads applied, the maximum error is ±0.4N. Both of these errors are small compared to the range of values for each test and have not been included in the above data.

Discussion

The work was carried out with an aim of comparing the mechanical stiffness of the 4 types of AFO. There are several differences between the test method used and the pattern of support and loading in gait.

In these trials the AFO has only minimal external support allowing all the AFOs to twist whilst dorsiflexing. When used during gait, the AFO would be supported internally by the leg and externally by the shoe, restricting the mode of deformation and possibly increasing the stiffness. The calculations have assumed an axis of rotation indicated by the malleoli prominences, however the actual axis of rotation of a foot/AFO combination is determined by anatomical and AFO structural considerations.

The strap added to the standard AFO consisted of the hook side of the Velcro stuck around the ankle and heel of the AFO, with the loop side fastened across the front. When loaded, the Velcro started to tear apart, to ensure continuity, the loop part was replaced for each test. This problem would be less likely to occur in clinical practice where a ‘D’ loop is employed since the load could be spread over a larger area when the strap is doubled back on itself. In addition the footwear being used will tend to provide additional support.

Both the carbon fibre and ridged AFOs present an increase in width across the ankle and foot, thereby making it more difficult to fit in standard shoes. The strap increases the width by a much smaller amount.

Although there were small differences in stiffness and ultimate moment carrying capacity observed between the carbon reinforced and structural strap designs it should be noted that only 1 of each design of AFO was tested so the differences may be due to small shape changes between the orthoses.

Note that care should be taken when using a structural strap such that it does not exert excessive forces on the patient and should not be used as compensation for over zealous cutting back of trimlines.

Conclusions

Using carbon fibre inserts to stiffen ankle foot orthoses is widely practised, however this work shows there is an easier to manufacture alternative that produces an AFO with similar resistance to dorsiflexion. These results were established whilst loading the AFO with no internal support, however, the results suggest there is enough evidence to warrant testing of the AFOs under more realistic loading patterns in a clinical environment.

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REFERENCES


