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Stiffness control in posterior-type plastic ankle-foot orthoses: effect of ankle trimline
Part 2: orthosis characteristics and orthosis/patient matching

T. SUMIYA, Y. SUZUKI, and T KASAHARA

Rosai Rehabilitation Engineering Center, Nagoya, Japan

Abstract

The hingeless plastic ankle-foot orthosis (AFO) changes stiffness largely depending on how much plastic is trimmed around the ankle. To support proper selection of the orthosis and final adjustment of the orthotic stiffness, the correlation between the posterior upright width and the resistance to dorsi- and plantar flexion movements was measured in 30 posterior-type plastic AFOs. The posterior upright width was varied by regularly trimming around the ankle in nine stages. The resistance to dorsi- and plantar flexion movements was measured by bending the plastic AFOs 15° with the measuring device described in Part 1. All the plastic AFOs decreased in their resistance to both movements in proportion to the reduction of the posterior upright width. The maximum resistance to plantar flexion movement was about 28 Nm, which was strong enough to assist dorsiflexion in patients with severe spasticity. On the other hand, the maximum resistance to dorsiflexion movement measured was about 10 Nm, which was insufficient to stabilise the ankle in patients who lacked in plantar flexion strength. These findings suggested that this type of plastic AFO should be prescribed for patients who predominantly require dorsiflexion assist, and that the orthotic stiffness could be finally adjusted by trimming to exactly meet individual requirements.

All correspondence to be addressed to Tadashi Sumiya, MD, Rosai Rehabilitation Engineering Center, 1-10-5 Komei Minato-Ku, Nagoya-shi 455, Japan. Phone: (+81) 52-652-5831 Fax: (+81) 52-652-6275

Introduction

The plastic ankle-foot orthosis (AFO) assists the swing phase by maintaining the ankle in a neutral position, controlling plantar flexion immediately after heel contact to absorb the impact of body weight, and supporting forward propulsion of the body by stabilising the ankle during terminal stance. It also controls eversion and inversion to provide adequate mediolateral stability.

Plastic AFOs without ankle joint articulations provide these functions in relation to the stiffness of the plastic around the Achilles tendon region. The ankle trimline is the most important among the several factors which affect the stiffness (Stills, 1975; Stills, 1977). Final adjustment of the ankle trimline is needed to meet the individual patient's requirements exactly even with proper selection of orthosis.

There are prescription criteria provided for plastic AFOs without quantitative data to define the final adjustment (LeBlanc, 1973; Lehmann, 1979; Lehneis *et al.*, 1973; Sarno and Lehneis, 1971; Sarno, 1973). The influence of the ankle trimline on orthotic stiffness has been evaluated without consistently regulating the trimming form (Condie and Meadows, 1977; Lehmann *et al.*, 1983; Rubin and Dixon, 1973) The objective of this research was to analyse quantitatively the change in orthotic stiffness corresponding with regulated ankle trimlines, and to advance prescription criteria. The posterior-type of AFO was selected for analysis because of its high frequency of prescription (Ofir and Sell, 1980; Sumiya *et al.*, 1993).

Materials and methods

Laboratory experiments

Two experienced orthotists fabricated 30 posterior type plastic AFOs, 24 for patients and 6 for healthy adults, from 3 mm thick standard grade polypropylene using the vacuum forming technique. The proximal trimline was set 3 cm below the fibular head and the distal trimline was extended to the end of the toes.

The ankle axis was positioned as shown in Figure 1 to serve as a fulcrum for bending the orthosis with a lever. Although this axis did not coincide with the anatomical ankle axis (Isman and Inman, 1969), it was considered from previous test experience to be appropriate. The following opinions support this consideration. The talocrural and subtalar joints act together to create a universal joint-like linkage between the leg and the foot (Wright *et al.,* 1964). However, the orthotic ankle axis allows the talocrural joint alone to move. Accordingly, orthotic and anatomical ankle axes should not be congruent (Kubota, 1981).

Ankle trimlines consisted of circular arcs and their tangents (Fig. 2a). The centres of the arcs were placed on the ankle axis as defined above. The tangents and other straight lines were extended to complete the entire trimline according to the dimensions of the orthosis. The nine different radii, 20%, 25%, 30% . . . , 60% of the lateral malleolus height, provided the nine-stage trimlines.

Endoskeleton below-knee models were prepared for each plastic AFO to be dorsi- and plantar flexed artificially in a manner which resembles actual deformation during walking (Fig. 2b). The leg and foot parts were moulded from plaster and fixed to the plastic AFO with a calf-strap and screws. The leg part slid smoothly along the pipe by using a lubricant.

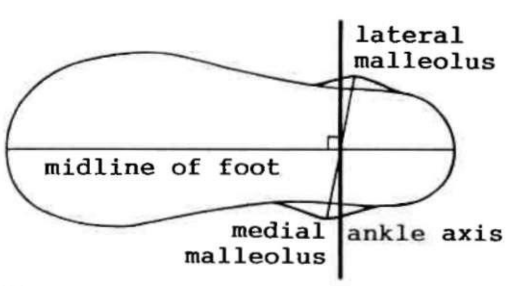

Fig. 1. The location of the ankle axis in a horizontal plane at lateral malleolus height.

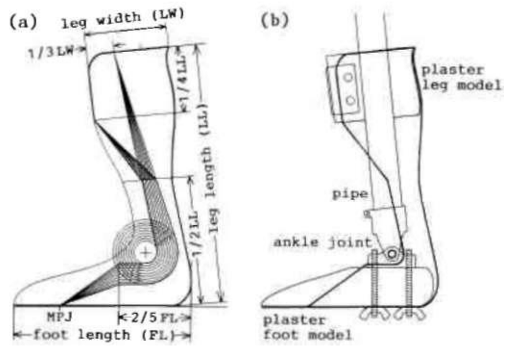

Fig. 2. (a) The nine-stage ankle trimlines.
(b) The endoskeleton below-knee model coupled with the plastic AFO.

The orthosis-model complex was placed horizontally , as described in Part 1, to eliminate the influence of gravity on the ankle movements (Fig. 3). The ankle was dorsi- and plantar flexed 15° at intervals of 2.5°, similar to the normal ankle angle range during walking (Peizer *et al.,* 1969; Stauffer *et al.,* 1977; Sutherland *et al.,* 1980). The ankle movement was measured 10 times at each angle. The orthosis was permitted to recover by leaving appropriate intervals between the measurements.

Simultaneous clinical assessment

A 55 year-old male with left sided hemiplegia, one of the 24 patients, wore the nine-stage trimmed orthosis. He had severe spasticity in the affected limbs with limited ankle dorsiflexion range. Careful observation of gait patterns and interview questions were made at each trimline stage to determine the optimal trimline for this particular patient.

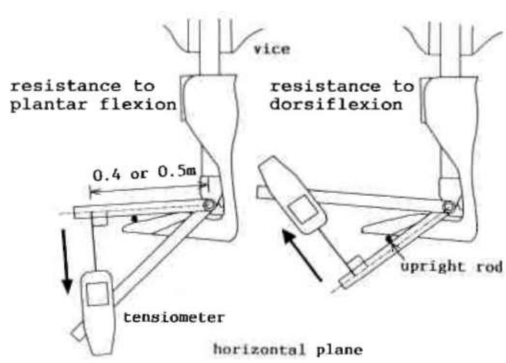

Fig. 3. The system of measurement. The resistance to plantar flexion movement indicated dorsiflexion moment. Similarly, the resistance to dorsiflexion movement represented plantar flexion moment.

Results

Laboratory experiments

A mean of 10 measurements was taken at each deflection throughout the experiments. The ankle moment measured with this device represents an approximately static situation.

The results of tests on 30 plastic AFOs are summarised in Figure 4, displaying the resistance to 5° and 15° of dorsi- and plantar flexion corresponding to each trimline stage. The results showed variation in the stiffness of the plastic AFOs. Both resistance to dorsi- and plantar flexion movements decreased almost in inverse proportion to the trimline stages.

The maximum resistance to plantar flexion movement measured was 27.5 Nm, SD 7.2 Nm when plantar flexed 15°, whereas that to dorsiflexion movement was measured as 10.5 Nm, SD 2.7 Nm when dorsiflexed 15°.

Clinical assessment

The subject displayed changes in his gait pattern with changing trimline. Without an orthosis, the stance phase started with toe-contact. With a 20% trimmed orthosis, the stance phase started with heel-contact accompanied by rapid knee flexion. With 30% trimming, plantar flexion occurred immediately after heel-contact and dorsiflexion during the terminal stance became apparent. With 40%, he progressed forward smoothly with the ankle dorsiflexed during the terminal stance. With 50%, he could achieve heel-off just before pre-swing. With 60%, the stride length on the sound side increased, but stability during the stance phase on the affected side decreased and toe-dragging appeared at pre-swing.

Discussion

The above statements offer the biomechanical grounds for the interpretation of the results.

A locked ankle orthosis provides good toe clearance during the swing phase and spasticity inhibition for hemiplegics (Perry, 1969). However, the rigid plantar flexion stop makes the knee unstable by producing a flexion moment at heel strike. The dorsiflexion assist with spring reduces the knee flexion moment by plantar flexing at heel strike without accelerating spasticity (Lee and Johnston, 1973; Lee and Johnston, 1974). The requirements for dorsiflexion assist for toe clearance during the swing phase and for knee stabilisation at heel strike complement each other. The former should be set at a minimum to permit the latter in flaccid paralysis (Lehmann *et al.*, 1970; Lehmann, 1979; Lehmann *et al.*, 1986). These findings suggest that the orthotic dorsiflexion assist should be minimised such that the swing phase can be carried out safely.

The triceps surae muscle resists dorsiflexion to stabilise the ankle and the knee during the midstance (Perry, 1992; Simon *et al.*, 1978; Sutherland *et al.*, 1980), which contributes to

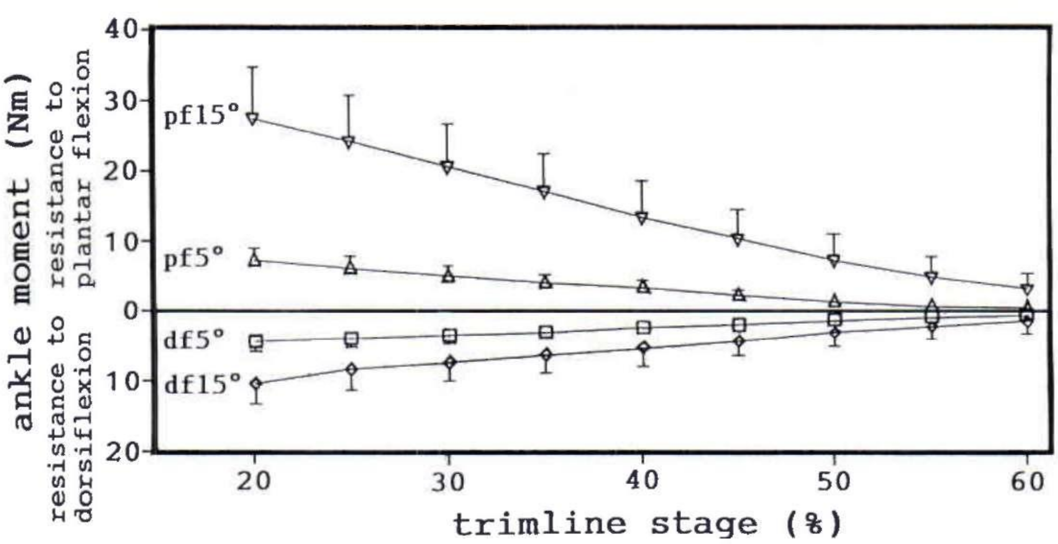

Fig. 4. The correlation between ankle moment and trimline stage. Dots and error bars represent mean and 1 standard deviation of 30 individual plastic AFOs.

forward propulsion of the body during the terminal stance (Brandel, 1976; Dubo *et al.*, 1976; Inman, 1966; Perry, 1974; Winter, 1983). The orthosis with anterior stop successfully substitutes for this muscle function in flaccid paralysis (Lehmann and Delateur *et al.*, 1980; Lehmann *et al.*, 1985; Perry *et al.*, 1995).

On the other hand there is no established indication for plantar flexion assist in spastic paralysis. Hemiplegic patients exhibit weak plantar flexors (Peat *et al.*, 1976). The anterior stop assists them to achieve heel-off, resulting in push-off phase elongation (Lehmann *et al.*, 1987). On the contrary, the hinged plastic AFO with free dorsiflexion reduces spasticity in children with cerebral palsy by stretching the Achilles tendon and saves quadriceps muscle energy consumption (Middleton *et al.*, 1988). Therefore, the orthotic plantar flexion assist should be determined comprehensively on the basis of muscle tone, gait pattern, and energy consumption.

The results can be interpreted based on the above considerations (Fig. 4). Curve-pf15° indicates the dorsiflexion assist at heel-strike for controlled plantar flexion, curve-pf5° curve the moment necessary for toe clearance during the swing phase, curve-df5° the resistance to dorsiflexion during the midstance for knee stabilisation, and curve-df15° the moment opposing free dorsiflexion during the terminal stance. These four requirements must be considered in matching the orthosis to the individual.

The maximum resistance to plantar flexion movement, about 28 Nm in curve-pf15°, is strong enough to control plantar flexion immediately after heel strike in patients with severe spasticity. However, the maximum resistance to dorsiflexion movement, about 10 Nm in curve-df15°, is insufficient to prevent the ankle from breaking down into dorsiflexion during the terminal stance in patients with complete plantar flexor paralysis (Lehmann *et al.*, 1985). In this case, reinforcement of the orthosis will be necessary to provide sufficient ankle support (Clark and Lunsford, 1978; Fillauer, 1981).

The availability of the four moment curves for the final adjustment of the ankle trimline is illustratively demonstrated in the case of the hemiplegic patient (Fig. 5). He required dorsiflexion assist exceeding 1.6 Nm (50% trimline) for toe clearance during the swing phase, but less than 14.4 Nm (40% trimline) for controlled plantar flexion at heel strike. Therefore, the trimlines from 40% to 50% produced the optimal dorsiflexion assist for this patient. On the other hand, he required as much ankle dorsiflexion as possible to transfer the centre of gravity forward during the midstance, overcoming the structural ankle stiffness (Thilman *et al.*, 1991). Consequently, the 50% trimline created the best condition in the posterior-type plastic AFO, and fortunately was a good match. An articulated plastic AFO with free dorsiflexion could possibly replace the

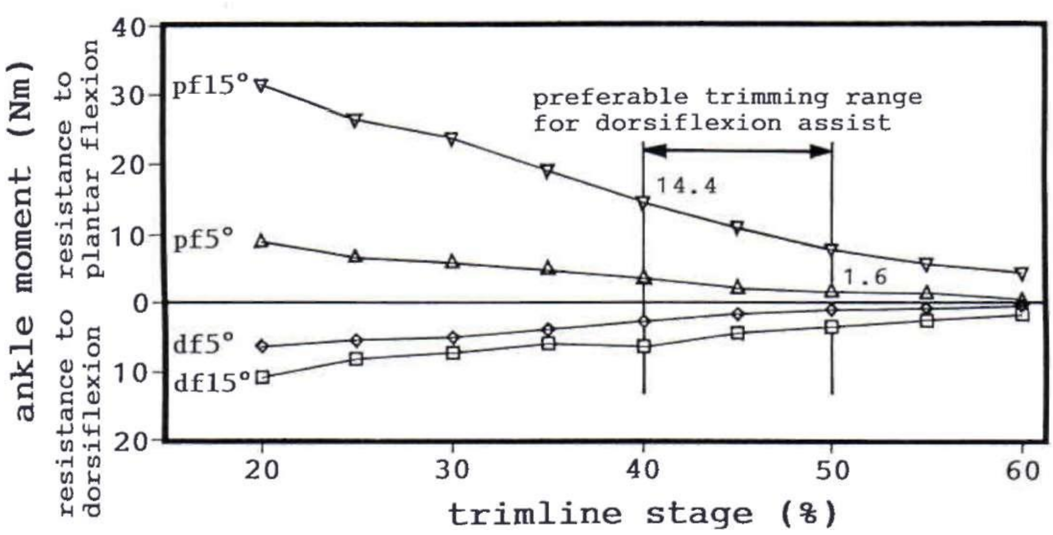

Fig. 5. Clinical application. Data of the hemiplegic patient's plastic AFO are shown.

posterior-type if the same resistance to plantar flexion was available.

Conclusion

The posterior-type plastic AFO decreased in resistance to dorsi- and plantar flexion movements nearly in proportion to the reduction of posterior upright width. The maximum resistance to plantar flexion movement was sufficient to assist dorsiflexion even under severe spasticity, but that to dorsiflexion movement was only about a third of the former. Accordingly plastic AFOs of this type should be prescribed for patients who predominantly require dorsiflexion assist, and the ankle stiffness must be adjusted by trimming to provide the optimal degree of support.

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