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The Influence of Heel Design on a Rigid Ankle-Foot Orthosis

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In the past decade measurements have been obtained on the forces exerted by ankle-foot orthoses (AFO's) on the lower limb. This quantitative information has been used to assess the effect of the orthosis on stability, mobility, and weight transfer of the patient. Orthoses which block plantar flexion impart a destabilizing knee flexion force with weight acceptance (1). As the normal unbraced limb is loaded following heel strike, the foot plantar flexes passively to 15 degrees because posterior protrusion of the heel helps create a lever between the point of floor contact and the axis of the ankle. Because the ankle is a freely moving joint, the immediate effect of the heel lever in response to initial floor contact is to cause the forefoot to rotate towards the floor. The controlled drop into plantar flexion serves as a shock absorbing mechanism that lessens the impact of initial contact with the floor.

When the ankle is "locked" in a rigid orthosis, the leg and foot pivot forward as a unit about the point of heel contact. The orthosis imparts to the posterior tibia a flexor bending moment at the knee or a tibial advancement torque. To maintain knee extension, the torque must be resisted either through muscular force or the orthosis must be modified to absorb some of the torque.

Tibial advancement torques have been measured quantitatively with strain gauges or tensiometers attached to the uprights of an orthosis. Lee (1) found that with a 90 deg plantar flexion stop there were two prominent pushing forces exerted by the calf band against the posterior calf, a force at heel strike and the other at push off. Lehman et al. (2) demonstrated that heel lever action at weight acceptance can be lessened by the insertion of a cushion wedge into the heel of the shoe as proposed by Eugene F. Murphy (3), or by cutting off the end of the heel.

To decrease destabilizing tibial advance torque a number of methods are used. The ankle joint can be plantarflexed but this causes toe clearance problems during swing phase and knee hyperextension during stance phase. More commonly a heel modification is used to decrease the destabilizing force at the knee during weight acceptance. The use of a heel modification allows the orthotist to decrease this force without compromising alignment.

Four methods of heel modification are frequently used to decrease destabilizing forces at heel strike:

• *SACH Heel*—This is an adaptation of the prosthetic SACH foot. A wedge of polyurethane foam is inserted in the posterior heel section and normal heel topping material is placed over it. This arrangement is very effective and durable, but requires a more extensive shoe modification than other solutions.

• *Beveled Heel*—The posterior heel is simply ground off at an angle. This expedient is effective, but many patients complain about the appearance and about having their new shoes altered by grinding material away.

• *Crepe Heel*—The entire heel of the shoe is replaced with a latex foam (crepe) material. It has good absorption qualities but tends to wear down quickly. Certain types of crepe will also leave marks on floors.

• *Standard Factory Hard Rubber Heel*—Patients usually prefer this type for cosmetic reasons.

This study was conducted in order to determine the relative effectiveness of the four methods with respect to decreasing the destabilizing forces at heel strike.

Methods

Subjects

A group of nine normal adults, four men and five women, were selected for the study. Their ages ranged from 19 to 46 years and each fitted comfortably into men's size 7-½ B oxford-type shoes. None had a history or presence of orthopedic or neurological disorders affecting the lower limbs.

Heel Design and Instrumented Orthosis

The subjects walked in an AFO locked at 90 degrees with each of the four heels under study:

Fig. 1. Anterior view of instrumented bichannel adjustable locking AFO.

• SACH—made with a medium density polyurethane center (the same material used for prosthetic SACH feet).

• Beveled—a hard rubber heel with the posterior edge rounded off. The bevel began 1 cm from the bottom of the heel and extended forward 3.5 cm from the posterior edge of the heel, creating an angle with the floor of approximately 20 deg.

• Crepe—made of latex and had an 'A' Shore hardness of 40.

• Hard Rubber—a standard factory heel with an 'A' Shore hardness of 74.

The heels were tested in a random but predetermined order to eliminate learning effects which might bias the data.

The shoes for the left side had adapted heels and stirrups with short shanks for attachment to a bichannel adjustable locking (Bicaal) type AFO (Fig. 1). The orthosis was adjustable in height and width to fit each subject properly. Strain gauges mounted on each upright made it possible to measure the bending moments exerted on the orthosis in the anterior and posterior directions of the sagittal plane during walking. On all subjects tested the moment arm extending from the ankle to the calf band was 25.4 cm.

Electrogoniometers, Force Plate and Foot Switch System

Knee and ankle electrogoniometers were used to measure sagittal motion of these joints (Fig. 2). The goniometers consisted of a double parallelogram linkage with a linear potentiometer attached to the proximal arm of the linkage. An overhead cable connected the instrumented orthosis and electrogoniometers to an FM analog tape recorder that provided a direct graphical readout.

The lateral, progressional, and vertical forces were measured as the subject walked across a force plate that was concealed with tiles.

The foot switch system provided quantitative information about the foot-floor pattern. Gait characteristics were calculated by relating the foot-switch data to time as the subject walked along a measured walkway. Contact-closing switches were placed in an insole under the heel, the heads of the first and fifth metatarsals, and under the great toe. The signals from the heel and metatarsal areas were coded as voltage levels. The resulting voltages were coded electronically so that the normal sequence for floor contact was displayed on paper as a staircase of equal height voltage steps. The toe switch presented an oscillatory pattern which could be superimposed on any of the other levels. All gait information was transmitted from the subjects to the recording system via a digital VHF radio telemetry system, recorded on video and analog tape, and printed on photosensitive paper.

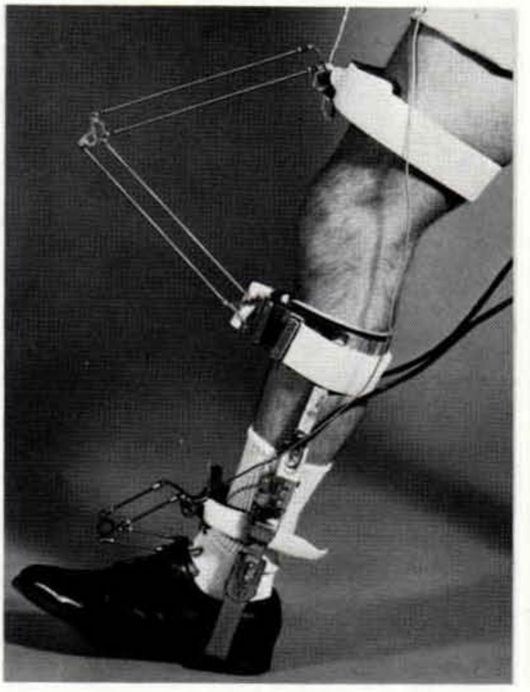

Fig. 2. Lateral view of instrumented AFO, knee and ankle goniometers.

Heel Hardness and Compressibility Testing

Heel durometer was determined by using a Model 302 Trionic Rubber Hardness Guide (Trionic Co. of America, Los Angeles, California). A force of 100 pounds was applied to the posterior edge of the SACH, crepe, and hard rubber heels at an angle of 20 deg which is similar in magnitude and angle of loading in normal walking. Linear deflection resulting from heel compression was measured for these three heel designs using a Rimac Spring Tester (Rinck, McIlwaine, Inc., New York, N.Y.).

Test Procedure

The subjects were given several minutes to become accustomed to walking with the orthosis and other electronic recording devices. Data were collected on two "runs" for each heel as the subject walked along the walkway. If the subject did not strike the force plate with the test limb, the test was repeated until adequate contact was made. No explanation was given to the subject.

Analysis of Data

Four consecutive heel strikes of the left limb were analyzed from both runs for each heel design. Data from each heel type were kept separated and a mean value was calculated for each dependent variable over all subjects. Heel designs were then compared to determine whether differences were not due to chance by using a "paired 't' test" at an acceptable level of significance of p .05. Variables measured and tested for significance among heel designs included:

1. heel contact tibial advancement torque;
2. knee flexion in response to loading;
3. ankle motion within the orthosis;
4. force plate recordings of lateral, progressional and vertical forces at heel contact;
5. stride length;
6. cadence;
7. velocity;
8. gait cycle duration;
9. single limb support time for both limbs; and
10. double limb support time.

Results

The magnitude of tibial advancement torque was determined by establishing a zero baseline while the subject was without the orthosis and by measuring the deflection from the baseline to the peak resulting from heel strike. The SACH, beveled, and crepe heels all had a shock absorbing quality and the tibial advancement torque imparted by these heels was significantly less than that of the hard rubber heel (Fig. 3). The hard rubber heel imparted a knee-flexion torque of 24.8 Newton meters (Nm). The torque produced by the SACH heel was 17.1 Nm, a 31 percent decrease when compared to the hard rubber heel. The beveled heel produced a torque of 18.8 Nm (a 24 percent decrease) and the crepe heel created a 21.8 Nm torque or a 12 percent decrease (Fig. 4). The reduction in the torque was the result of shortening the lever about the joint. By beveling the heel, the heel lever was shortened 1.3 cm. Heel compressibility tests demonstrated that the heel lever can also be shortened 1.3 cm in the SACH heel by applying a force of 445 N (100 pounds) to the posterior edge of the heel. When the same force

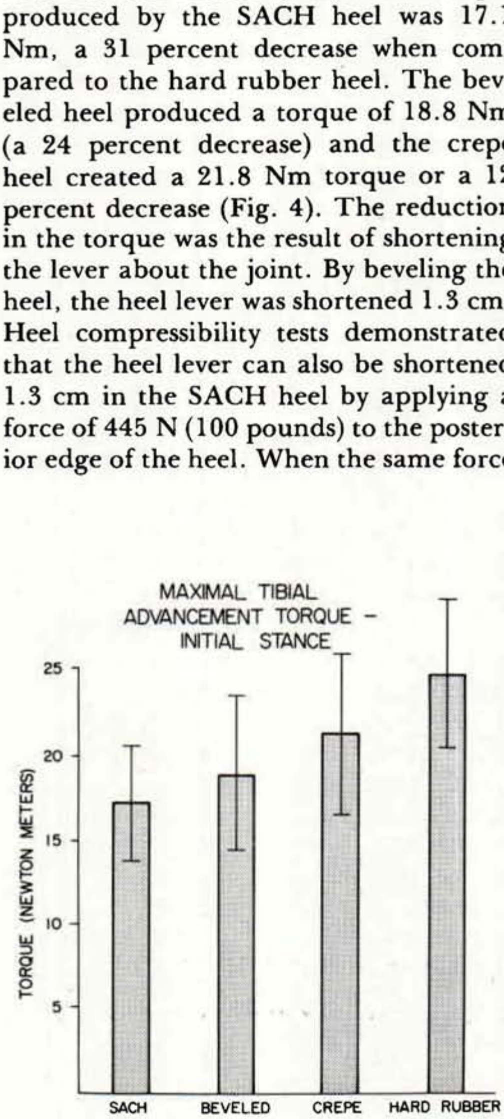

Fig. 3. Comparison of tibial advancement torques.

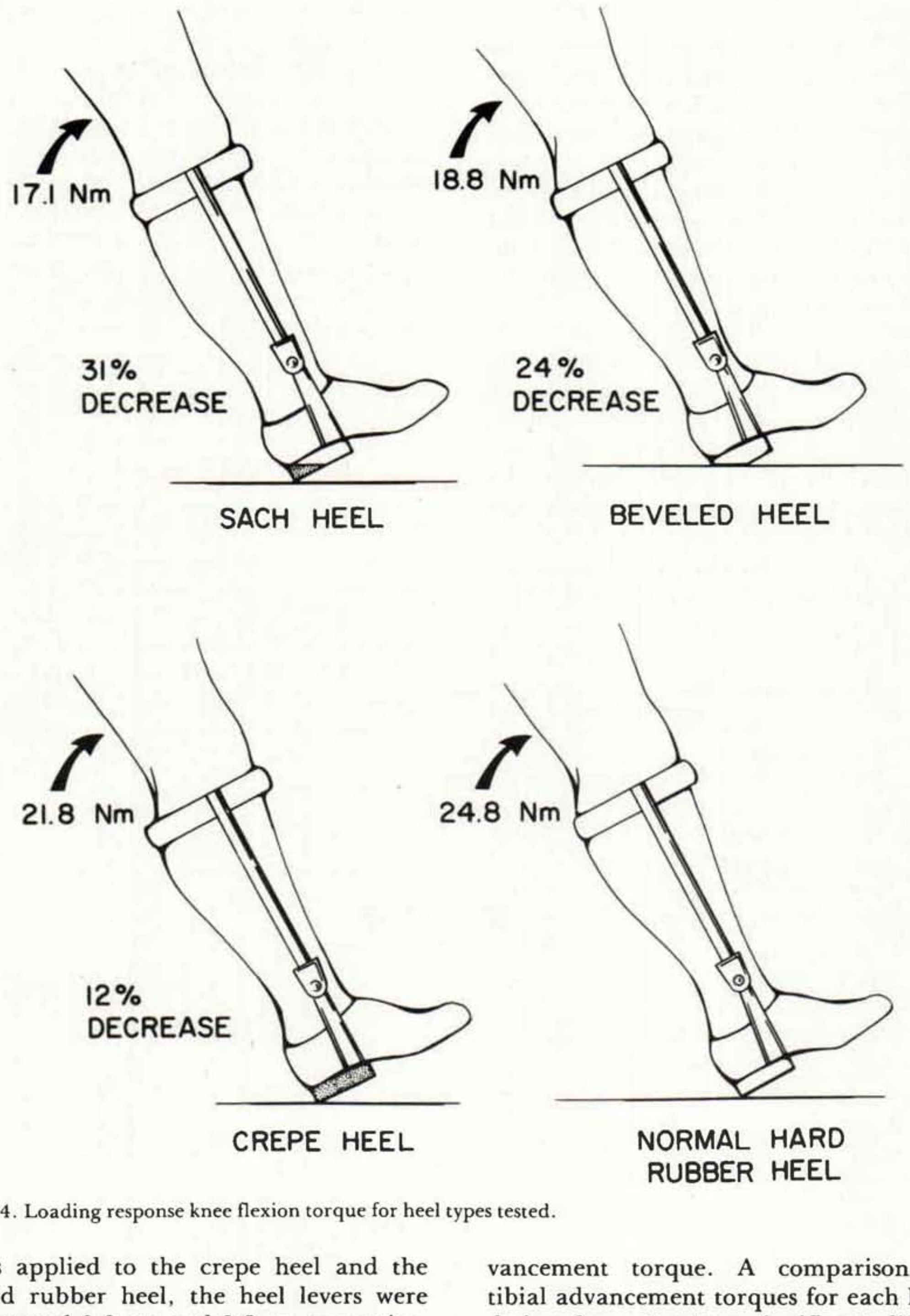

Fig. 4. Loading response knee flexion torque for heel types tested.

was applied to the crepe heel and the hard rubber heel, the heel levers were shortened 0.9 cm and 0.2 cm respectively. Thus, there is a direct relationship between heel lever length and tibial advancement torque. A comparison of tibial advancement torques for each heel design demonstrates a significant difference in all cases except when comparing the SACH to the beveled heel.

Every subject demonstrated a longer stride length when walking with a crepe heel than a beveled heel. This would indicate that stride length increases with a longer heel lever. Stride length tended to be shorter with the hard rubber heel than with a crepe or SACH heel, perhaps because of excessive knee flexion torque. In seven of the nine subjects tested, double limb support time was longest with the hard rubber heel (Table 1).

There were no significant differences among heel designs when considering knee and ankle motion, lateral, progressional and vertical forces, cadence, velocity, gait cycle duration, and single limb support time. It was observed that the subjects walked at a normal cadence with all heel designs but velocity was less because of a corresponding average decrease in stride length. Gait cycle duration and left single limb support time were normal.

There was an average of nine degrees of ankle motion within the locked AFO. A minimal percentage of the ankle motion occurred at heel contact but this motion was not affected by heel design. Most ankle motion occurred as the subject's center of gravity moved over the forefoot (maximal dorsiflexion) to toe off (maximal plantar flexion) of the braced extremity. This motion could have been decreased with a long shank which extended from the heel to the metatarsal heads.

Discussion

Trunk advancement is accomplished by changes in the foot-floor-ankle relationship of the stance limb. Perry (4) describes this relationship in terms of

GAIT AND FORCE MEASUREMENTS	HEEL DESIGN			
	SACH	Beveled	Crepe	Hard Rubber
Gait Characteristics				
Velocity (cm/sec)	121.1 ± 12.2	122.5 ± 14.7	125.7 ± 14.8	122.0 ± 13.2
Stride length (cm)	133.1 ± 8.2	131.0 ± 7.8	135.2 ± 9.1	132.5 ± 6.8
Cadence (steps/min)	109.0 ± 9.0	112.0 ± 12.0	112.0 ± 11.0	111.0 ± 10.0
Gait cycle duration (sec)	1.07 ± .10	1.08 ± .13	1.09 ± .11	1.09 ± .10
Single limb support				
braced limb (%gc)	39.7 ± 1.6	39.9 ± 1.9	40.2 ± 1.7	39.2 ± 1.6
unbraced limb (%gc)	41.7 ± 2.4	41.6 ± 2.8	42.4 ± 2.5	39.9 ± 3.2
Double limb support (%gc)	18.5 ± 2.6	18.6 ± 2.2	17.6 ± 2.0	20.9 ± 3.1
Knee flexion as result of limb loading (degrees)	12.0 ± 5.0	11.0 ± 4.0	12.0 ± 5.0	11.0 ± 6.0
Force Measurements				
Tibial advancement torque at limb loading (Newton)	17.1 ± 3.3	18.9 ± 4.6	21.2 ± 4.8	24.8 ± 4.4
Lateral force (Newton)	48.9 ± 10.7	49.4 ± 8.9	53.8 ± 16.0	48.5 ± 8.9
Progressional force (Newton)	80.5 ± 22.7	85.4 ± 20.0	86.7 ± 13.3	74.3 ± 15.6
Vertical force (Newton)	676.0 ± 89.0	681.0 ± 89.0	681.0 ± 93.0	681.0 ± 98.0

Table 1. Gait and force measurements of normal subjects walking in locked AFO with four heel designs. Mean values of nine women and women.

three rockers, each serving to advance the swing limb through part of the total arc. The initial rocker occurs during limb loading and allows forward rotation of the tibia as a result of the heel level action. Tibial advancement torque is a measurement of this initial rocker magnitude. Since a majority of the patients for whom a rigid AFO is prescribed have marginal knee stability, added tibial advancement torque is objectionable. It has been demonstrated in this study and by Lehman (2) that tibial advancement torque can be reduced by use of a cushion or beveled heel. Limb loading compresses the heel, thereby shortening the length of the heel lever and provides a shock absorbing effect as well as a substitute for loss of plantar flexion in loading response. Modification of the heel is only effective for patients who initially contact the floor with the heel and will therefore have no effect on patients with a toe-first or flat-foot gait.

Midstance rocker action occurs during the midstance phase of the gait cycle or while the foot is flat on the floor. Trunk advancement in this phase results from a forward motion of the tibia through an arc of 25 degrees. Fixed ankle plantar flexion blocks the mid-stance rocker action entirely. Therefore, the degree of trunk advancement that can be accomplished during midstance is dependent upon the amount of substitution available at the hip or knee. If the knee lacks hyperextension range or the patient cannot afford hip flexion because his extensor muscles are too weak to support this posture, the patient will have a step-to rather than a step-through gait. The normal subjects tested had a 12 percent decrease in stride length when walking with a locked ankle orthosis because of diminished midstance rocker action.

Terminal rocker action occurs during terminal stance as a result of body advancement over the forefoot with the ankle locked. Terminal heel rise combined with a forward roll of the tibia during weightbearing is the sign of adequate terminal rocker action. Rigid ankle bracing can provide for adequate terminal rocker action even with minimal plantar flexion strength.

Summary

Four different heel modifications on shoes attached to a rigid ankle-foot orthosis were tested on nine normal patients. The purpose of the study was to determine which type of heel modification was most effective in decreasing tibial advancement torques generated from initial contact through the loading response phases of gait. The heel modifications were compared to a normal hard rubber heel on the same orthosis.

- The SACH-type Heel was the most effective of the four heel modifications. Knee flexion movement decreased to 17.1 Nm, a 31 percent decrease when compared to the hard rubber heal.
- The Beveled Heel effectively decreases knee flexion movement to 18.8 Nm by providing a shorter heel lever arm, a 24 percent decrease when compared to the hard rubber heel.
- The Crepe Heel absorbed shock by a significant amount, providing only a 21.8 Nm torque to the knee, a 12 percent decrease when compared to the hard rubber heel.
- The Hard Rubber (normal) Heel imparted the most destabilizing knee flexion torque, 24.8 Nm.

These heel modifications are recommended for patients who initially contact the floor with the heel and who may have knee instability problems due to muscular weakness or proprioceptive impairment and should not be used automatically on every rigid ankle-foot orthosis.

Footnotes

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