# UC-BL DUAL-AXIS ANKLE-CONTROL SYSTEM: ENGINEERING DESIGN [a] [b]

Larry W. Lamoreux, M.Eng.

Postgraduate Research Engineer
Biomechanics Laboratory
University of California San Francisco Medical Center
San Francisco, Calif. 94122

*Note: Excerpts from the article "The Orthotic Prescription Derived from the Concept of Basic Orthotic Functions" are included here in an effort to present this report in a more complete form.*

The Editors.

## ABSTRACT

The conventional ankle brace permits movement at the ankle complex about a single axis of rotation only. Studies of the literature and of cadaver dissections suggested that provision for rotation about two separate axes would result in a more functional ankle brace. An instrumented adjustable dual-axis external analog of the ankle complex was constructed to permit experimental examination of the functional attributes of a dual-axis brace and of the effects of misalignment between respective brace axes and anatomic axes. Conclusions were that proper alignment is very important and, furthermore, that the properly aligned dual-axis ankle brace offers substantial improvements in function and comfort over the single-axis brace.

The objectives of the engineering design were fourfold:

1. to develop practical and economical brace hardware;
2. to establish procedures for determining the optimum locations for the brace joints;
3. to provide a method for achieving this optimum alignment in the finished brace;
4. to devise a system for recording the configuration of a finished brace for future reference.

Optimum alignment is determined empirically with use of an adjusta-

[a] Based on work performed under VA Contract V1005M–2075.

[b] Also published as: Lamoreux, L. W.: UC-BL Dual-Axis Ankle-Control System: Engineering Design. Biomechanics Laboratory, San Francisco and Berkeley, Technical Report No. 54. San Francisco, The Laboratory, January 1969.

ble brace. Duplication fixtures were developed to insure accurate transfer of alignment to the finished brace.

Principles of alignment derived from this study are generally applicable to the evaluation of the alignment of any ankle-brace system.

## THE ORTHOTIC DEVICE: A DEFINITION

An orthotic device is an appliance which is designed to apply forces to the human body in a controlled manner in order to accomplish specific functional or therapeutic goals in the management of musculoskeletal disorders. The nature of the forces and the manner in which they are applied will vary greatly depending on the particular disability involved and the goals to be achieved, but in every case the effects of the orthotic device are a direct result of the forces which it applies to the body (*1*).

Many factors influence successful treatment with an orthotic device, but none is more important than an understanding, on the part of the physician who prescribes the device and the orthotist who makes it, of what it can and cannot be expected to accomplish. The names of orthotic devices are usually not of much help in establishing such an understanding; for example, short leg brace, long leg brace, Milwaukee brace, or Denis Browne splint; nor are the common classifying descriptions, such as supporting, correcting, or stabilizing. A simpler and more precise basis for describing the requirements, capabilities, and limitations of orthotic devices is needed.

One possibility is a description based on function. In all orthotic devices the forces which are applied to the body are utilized to perform one or more of the following three basic orthotic functions (*1*):

1. to support body weight;
2. to control joint motion (direction, range, strength)
    a. by limiting motion (partially or wholly),
    b. by restoring motion (partially or wholly);
3. to change the shape of body tissues
    a. by bending or twisting bone structures,
    b. by stretching soft tissues.

An orthotic device cannot be expected to perform any other function, and any proposed orthotic device can be described in terms of the specific combination of these basic orthotic functions which it is intended to perform.

## CONTROL OF FORCES

The forces applied by the device should be controllable so that the comfort of the wearer can be provided for and the effects of the device

anticipated. Not only the achievement of desired results but also the avoidance of undesirable side effects, such as increased deformity, depend on the ability to control the forces that are applied. One method of insuring control over these forces, in a device which must span one or more anatomic joints, is to build the basic structure of the device in such a manner that the framework alone does not apply any forces to the body but does provide a means of applying those forces which are desired. The resulting device follows any and all anatomic movements without any interference except that which is intended. In theory, at least, such a device could be built by making its basic structure analogous, or kinematically equivalent, to the structure of the corresponding part of the skeletal system. For every link or joint of the skeletal structure there would be, then, a corresponding link or joint in the analog. With such an external mechanical analog superimposed on the skeleton in such a manner that each pair of corresponding joints is coaxial, the two systems will be completely equivalent and there will be no discrepancies in motion, hence no interference forces, between the body and the external analog. Such an approach is sound in theory but is not necessarily possible in practice because of the differences between mechanical and anatomic joints.

## ANATOMIC JOINTS AND THE NEED FOR COMPROMISE

The designer of articulated orthotic devices has always been troubled by the complexities of anatomic joints. Motions which occur at the freely movable joints of the body and its extremities are influenced not only by the shapes of the joint members and by constraints due to joint capsules, ligaments, and tendons, but also by any external loads which may be transmitted through the joints. As a result, the patterns of motion of anatomic joints are usually complex and variable, with little more than superficial resemblance to common mechanical hinges. This complexity frequently forces the designer to make simplifying approximations or assumptions about the nature of the movements of anatomic joints in order to arrive at practical design criteria for othotic devices. The accuracy of these approximations can be expected to determine the accuracy of any designs based on them. As a consequence, the acceptability of any given approximation will depend on the amount of error that can be tolerated without sacrificing the original design objectives.

## THE ANKLE COMPLEX AND ITS ANALOG

This report is primarily concerned with control of motion in the ankle complex, and that region of the body will serve as the basis for an illustration. A number of joints are involved in the connection between

leg and foot, and, strictly speaking, none of these is a simple, single-axis joint like a mechanical hinge. Because of the complexity of the foot/ankle mechanism and the individual structural variations which exist, it is not practical to build articulated ankle braces which exactly duplicate the intricate movements of the anatomic system. Compromises must be made in the interest of simplicity. The question is, what simplifying approximations are acceptable for purposes of brace design?

The conventional ankle brace (Fig. 1) provides a single axis of rotation for movements of the foot and leg relative to each other. Implicit in such a design is the simplifying assumption that, for purposes of brace design, the multiaxis anatomic ankle can be replaced or approximated by a single axis of rotation. A moment's reflection on the motions which can occur in a normal ankle suggests that this is a rather gross approximation, and one which can be expected to give rise to substantial "errors," or discrepancies, between the motions of the single-axis ankle brace and the leg to which it is attached. Whether or not such discrepancies are satisfactory or unsatisfactory in a given situation depends upon the original objectives of the device. The large numbers of single-axis ankle braces in use today testify to the fact that such a crude approximation may often be a satisfactory basis for orthotic design. The

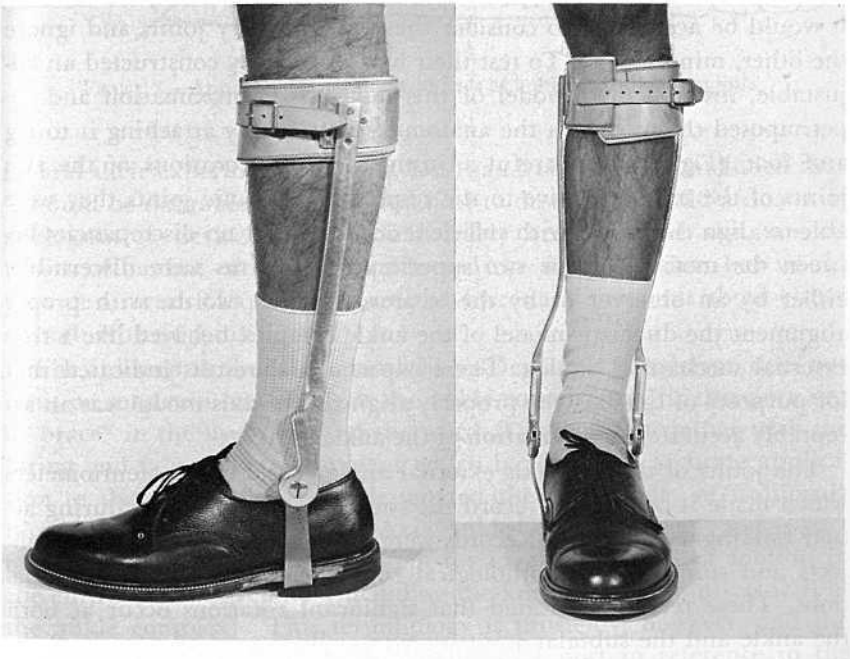


FIGURE 1.—Conventional ankle brace.

problems of restricted motion and discomfort which sometimes arise with the use of the conventional ankle brace indicate, however, that there is also a need for a brace which is based upon a more precise approximation.

Certainly, more precise approximations than that of the single-axis ankle are possible, but any increase in the accuracy of the approximation can be expected to result in an increase in complexity of devices based upon it. Desai and Henderson investigated this problem of reconciling simplicity with accuracy in the design of ankle braces (*2*). After studying the motions which occur between the leg and the foot (by surveying the existing literature and examining cadaver material) they observed that this region comprises three main functional parts: the leg (tibia and fibula), the foot (phalanges, metatarsals, and all tarsals except the talus), and the link which connects the two—the talus. Of all the many joints in the foot and ankle complex, the two closely associated joints which connnect these three main parts together account for most of the motion that normally occurs between the leg and the foot. These are the ankle (talocrural, upper ankle) joint connecting the talus to the leg, and the subtalar (lower ankle) joint connecting the foot to the talus. The approximate locations of the axes of these joints (*3, 4, 5*) are shown in Figure 2.

Desai and Henderson hypothesized that for purposes of brace design it would be acceptable to consider these two primary joints and ignore the other, minor joints. To test their hypothesis they constructed an adjustable, instrumented model of this dual-axis approximation and superimposed the model on the anatomic structures by attaching it to leg and foot (Fig. 3). By careful adjustment of the locations of the two joints of the model relative to the respective anatomic joints they were able to align the model with sufficient accuracy that no discrepancies between the motions of the two superimposed systems were discernible, either by an observer or by the wearer. In other words, with proper alignment the dual-axis model of the ankle complex behaved like a true external mechanical analog. These experimental results indicated that for purposes of bracing, the properly aligned dual-axis model was an acceptably accurate approximation of the ankle complex.

The joints of the dual-axis external analog contained potentiometers which made it possible to record the rotations of both joints during actual walking (see Fig. 3). Records were obtained, for both normal subjects and subjects with pathological conditions, in a variety of situations. These records indicated that significant rotations occur at both the ankle and the subtalar joints during walking, even during walking on a flat and level surface (Fig. 4). On the basis of their original stud-

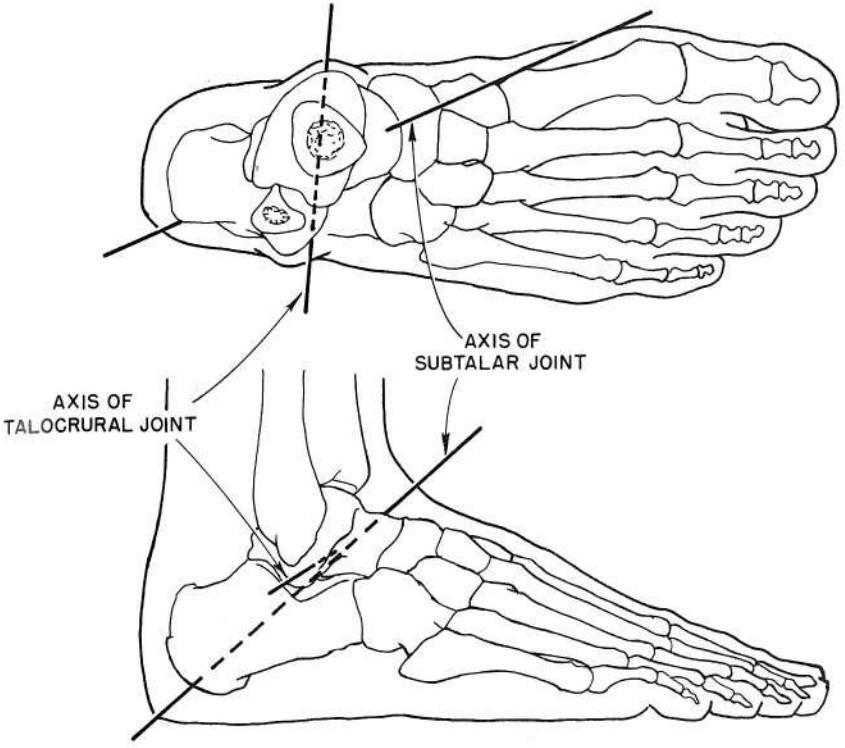



FIGURE 2.—Approximate locations of axes of ankle and subtalar joints.

ies and their experimental results, Desai and Henderson concluded that it would be desirable as well as practical to design and build a dual-axis ankle-control device which would freely accommodate the normal ranges of motion of both the ankle and the subtalar joints but would provide a means of applying corrective forces and moments about either or both of these joints.

The ankle-control device conceived by Desai and Henderson does not limit or constrain movement at the ankle complex and is therefore not a "brace" in the usual sense of the word. The device, together with the fitting and fabrication equipment which facilitates its accurate application to the wearer, has been designated the "University of California Biomechanics Laboratory Dual-Axis Ankle-Control System" and is part of a planned comprehensive system for external control of motion in the entire lower extremity (including the knee and hip joints as well as the ankle complex). This terminology is unwieldy, however, and the term *brace* will sometimes be used in this report in reference to the dual-axis ankle-control device.

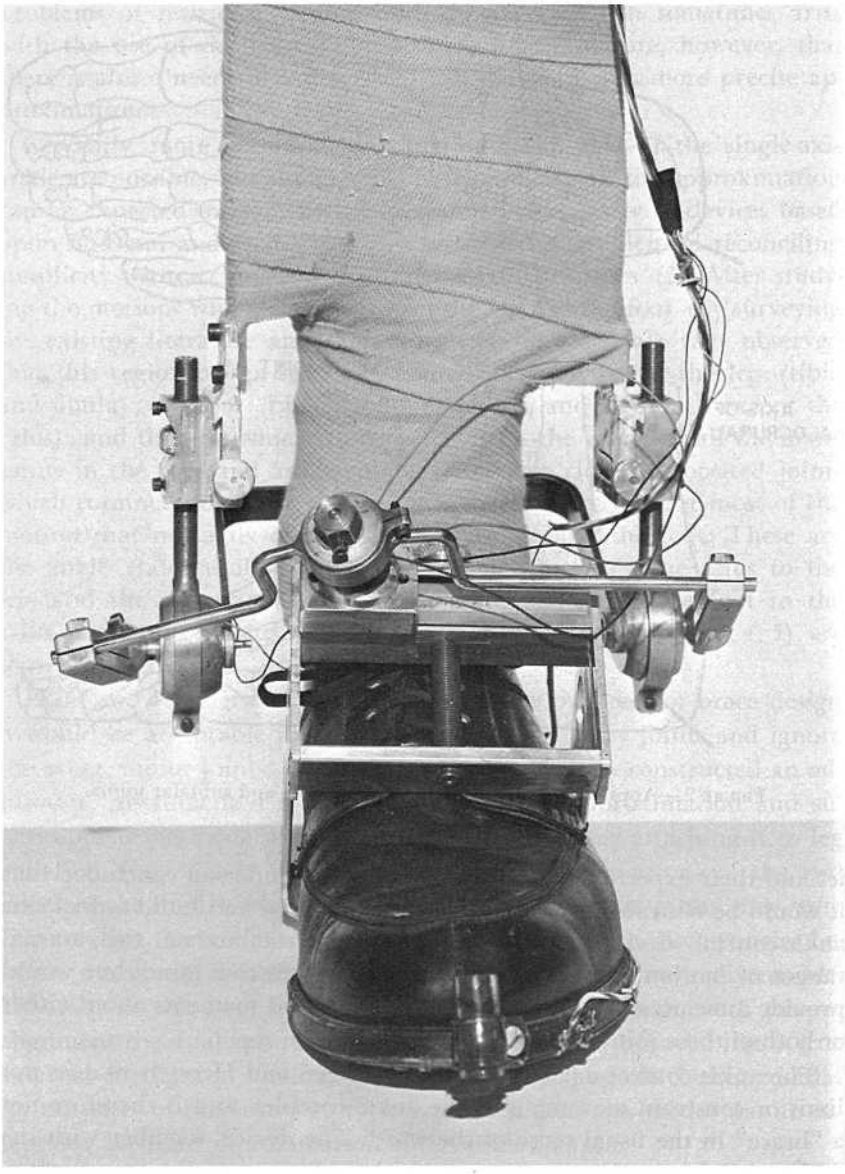


FIGURE 3.—UC-BL instrumented adjustable external analog of the ankle complex.

## APPLICATION OF THE DUAL-AXIS CONCEPT

The original brace designed by Desai and Henderson has been described in detail (*2*). In its final form (Fig. 5) it had the external equivalent of the subtalar joint ("analog" subtalar joint) attached to

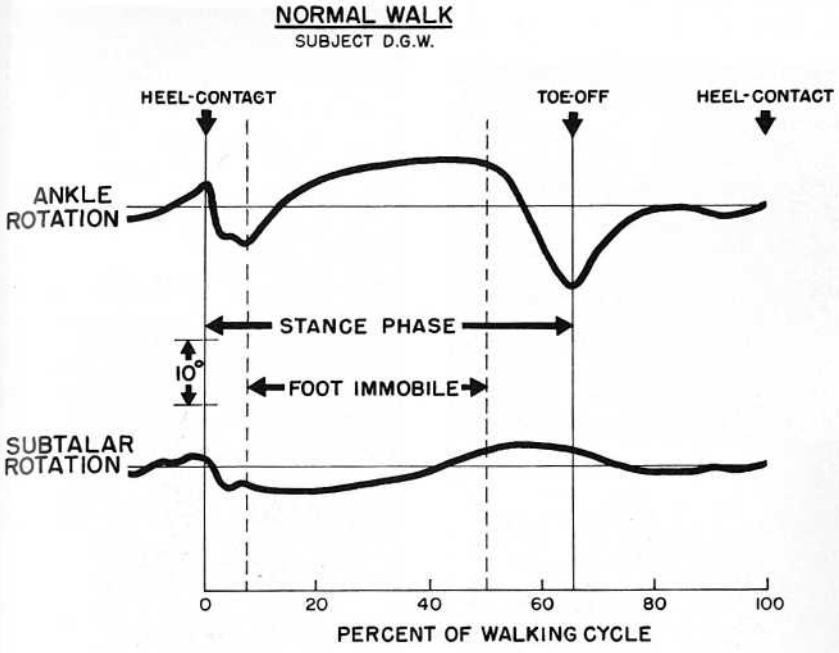



FIGURE 4.—Records of rotation at ankle and subtalar joints, obtained with use of instrumented external analog. (Reprinted, with permission, from J. Bone Joint Surg., 46–A: 361–383, March 1964.)

the shoe posteriorly with the joint axis inclined so that it passed approximately through the center of the ankle complex. This joint was connected to the analog ankle joint (the joint of a commercial toe-lift sidebar) by means of a laterally placed metal coupling link which is the external equivalent, or analog, of the talus. The single sidebar was attached to a calf band in a conventional manner.

Other joint configurations are described by Desai and Henderson and some other configurations have been examined since their report was published, but experience with their "improved second design" (Fig. 5) has demonstrated the functional and cosmetic desirability of their chosen configuration for a drop-foot brace in which the loads applied to, or by, the brace are small.

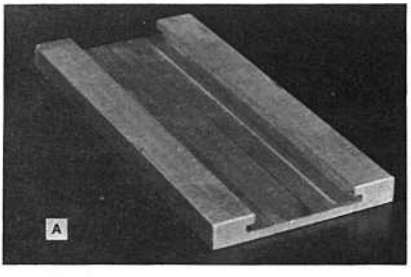
The ankle-control system described in this report is not intended to be an "all-purpose" brace. It is suitable only for those cases in which relatively small moments are required for control of the ankle and subtalar joints. In its present form (Fig. 6), it *cannot* be used for bearing weight or positively limiting motion because the structure and joints have not been designed for the heavy loads which would result from such use. There is no theoretical reason, however, why the same con-

FIGURE 5.—"Improved second design" of brace (Desai and Henderson).

FIGURE 6.—Current design of dual-axis brace.

cepts could not be employed in the design of a more rugged dual-axis ankle unit which would be suitable for use in a weight-bearing brace. The problems in such a design are practical ones, related to size, weight, appearance, and fabrication.

The choice of terminology for the components of the brace has been somewhat arbitrary and should be explained. A *channel* (Fig. 7) of aluminum or plastic is permanently mounted in the heel of the patient's shoe to permit attachment of the brace to the shoe. The *stirrup* (Fig. 8) slides into this channel to connect the analog subtalar joint (*heel*



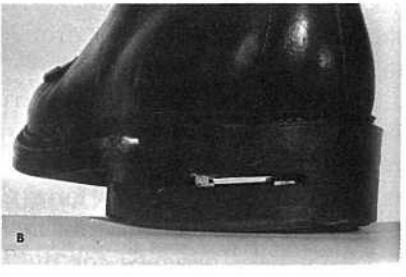




FIGURE 7.—Channel. *A*, part as received; *B*, installed in shoe.

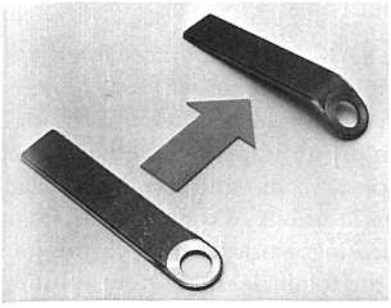
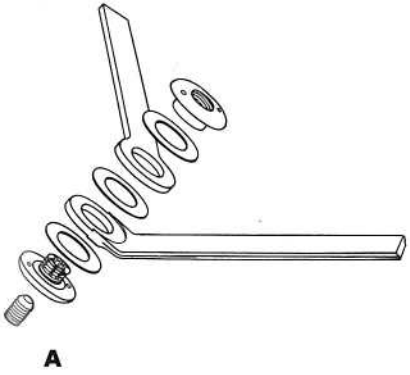


FIGURE 8.—Stirrup, before and after bending.



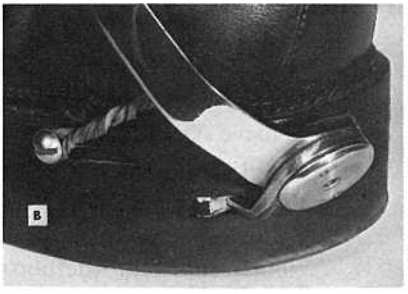




FIGURE 9.—Heel joint. *A*, exploded view; *B*, assembled.

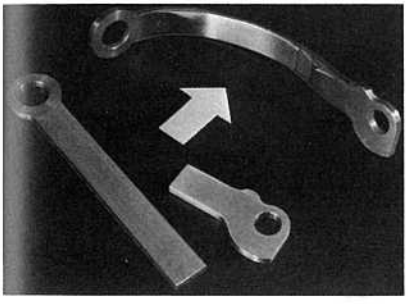


FIGURE 10.—Yoke, before and after fabrication.

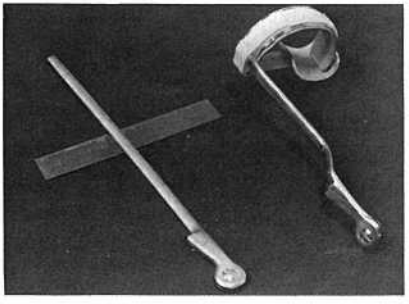


FIGURE 11.—Sidebar and calf band, before and after assembly.

*joint*) (Fig. 9) to the shoe. The external analog of the talus is called the *yoke* (Fig. 10); it connects the heel joint to the analog ankle joint (*sidebar joint*). The upright member is known as a *sidebar* (Fig. 11); it carries the *calf band,* or *calf cuff,* which surrounds the calf of the wearer. More details are defined in the discussion of the design of specific components to be found in Appendix I.

## DESIGN OBJECTIVES

Some mechanical problems with the early dual-axis brace design were encountered (primarily a lack of durability of the joints) but it became apparent very early in the development that eventual widespread application would depend on more than simply an improved mechanical design of the brace. It would be necessary, in addition, to develop methods for accurately determining the locations of the anatomic joints in the ankle of a patient and for fabricating a brace in which the joint axes are accurately aligned with these anatomic axes. Without solutions to these problems, an improved model of the brace would not be of any great usefulness. Also desirable, though not essential, would be a method for permanently recording, either numerically or graphically, the configuration of a completed brace.

### Summary of Design Objectives

The objective of the dual-axis brace project, then, was to develop a comprehensive system consisting of four basic parts:

1. The brace proper: all the component parts necessary to assemble the brace.
2. An alignment technique: a systematic and simple, though sufficiently accurate, method for locating the axes of the anatomic ankle and subtalar joints.
3. Fabrication procedures: reliable methods and equipment for fabricating a finished brace with joints aligned with the determined anatomic joints.
4. Permanent record: a graphic or numerical method for permanently recording the characteristics and specifications of a finished brace.

The appendixes contain detailed discussions of the design of brace components, alignment aids, and fabrication fixtures, and describe methods for permanently recording the dimensions of the finished brace. The following paragraphs explain the principles of alignment of the dual-axis brace and describe the procedures for its fabrication.

## ALIGNMENT AND FABRICATION

Any device for determining the location of the anatomic joints of the ankle complex must not depend on the ability of the patient to judge whether or not the device interferes with free joint motion and should not even depend on the patient's active participation. An early aim of the development program was to devise a compact and portable instrument which would quickly, simply, and accurately locate the axes of a patient's ankle and subtalar joints. Fabrication fixtures then would be

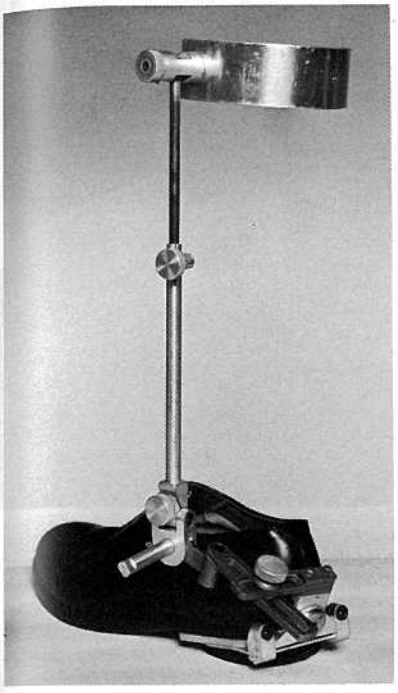


FIGURE 12.—Adjustable brace used for fitting and alignment.

built which could be adjusted according to the readings obtained from the instrument, and the components of the finished brace would be fabricated in these fixtures.

Considerable effort went into the attempt to develop such an "ideal" system, and some effort is still being directed along these lines, although primarily for purposes of fundamental motion studies rather than bracing. No system has yet been devised which shows much promise of being practical for widespread clinical use. A compromise approach was therefore undertaken which consisted of building an *adjustable-fitting brace* (Fig. 12–16) and a system of duplication fixtures (Fig. 17–19). The adjustable brace makes use of the same joint design as the actual finished brace which the patient eventually receives, but the shape of each link of the brace can be readily adjusted. The position of the stirrup on the shoe and the angle of inclination of the axis of the heel joint are both adjustable, as are the relative positions of heel and sidebar joints, and of sidebar joint and calf band.

The three main elements of the adjustable brace are the adjustable stirrup assembly (Fig. 14), the adjustable yoke assembly (Fig. 15), and the adjustable sidebar assembly (Fig. 16). These three elements are assembled with use of joint hardware of the same design as that used in

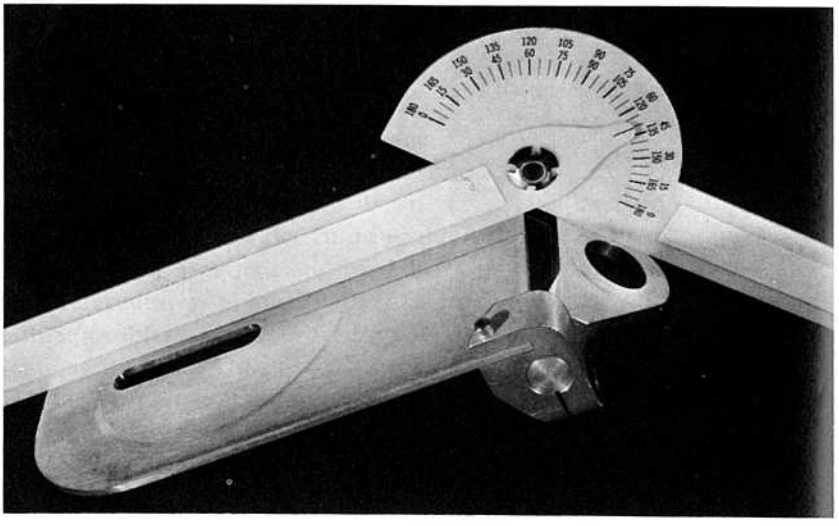
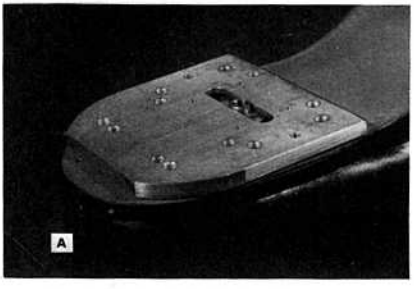
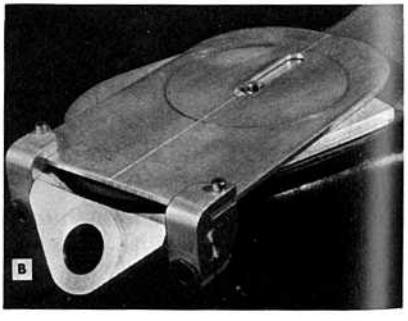


FIGURE 13.—Adjustable stirrup with protractor which shows bend angle.



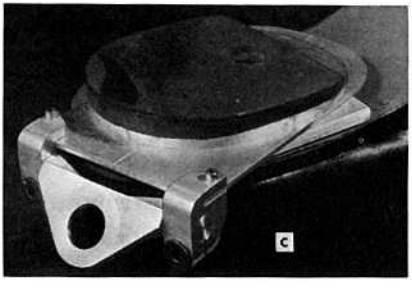




FIGURE 14.—Adjustable stirrup assembly. *A*, heel plate installed; *B*, adjustable stirrup in place; *C*, completed assembly with clamping plate and clamp screw in place.

the finished dual-axis brace, and they are adjusted to the patient by means of alignment procedures described below. The three elements of the adjustable brace are then disjointed from each other again and individually duplicated to form the standard brace parts which will make

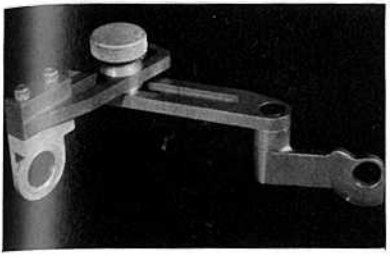


FIGURE 15.—Adjustable yoke assembly.

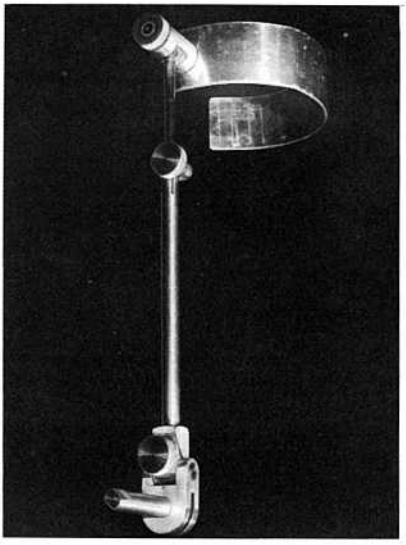


FIGURE 16.—Adjustable sidebar assembly.

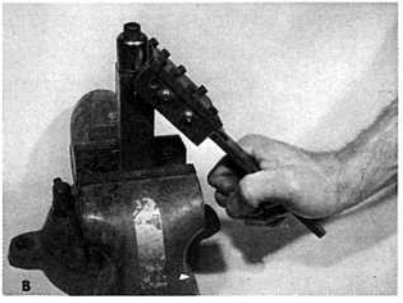



FIGURE 17.—Stirrup bending fixture. *A*, parts; *B*, in use.

up the patient's finished appliance. The finished brace (Fig. 6) is no longer adjustable, but its joint alignment is the same as that of the properly aligned adjustable brace. Appendix II contains a more detailed description of the adjustable brace and the alignment duplication fixtures.

## OBJECTIVES OF ALIGNMENT

The objectives of alignment of the dual-axis brace derive from the analog concept of joint control upon which the brace is based. Recall that the dual-axis brace is an external structure which is superimposed on the anatomic structure of the leg, ankle, and foot. Its two joints corre-

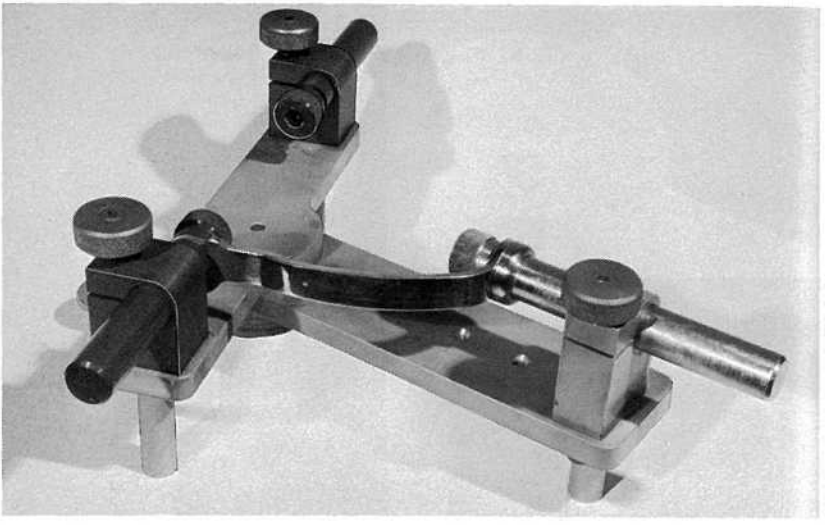


FIGURE 18.—Yoke duplication fixture with completed yoke in place.

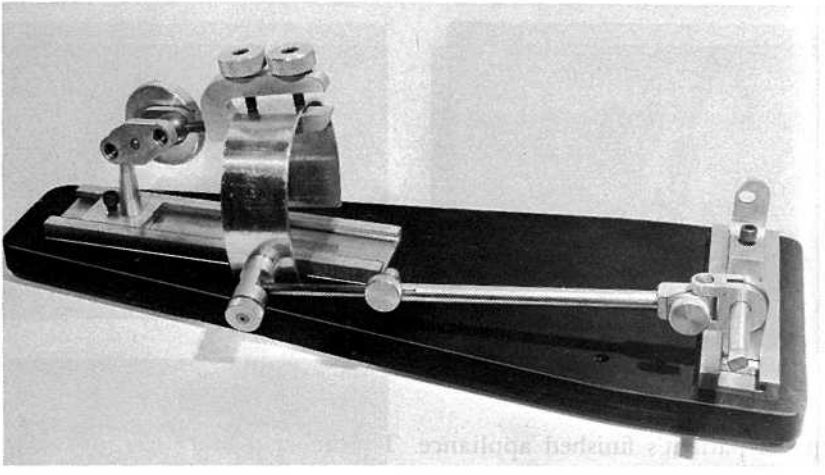


FIGURE 19.—Calf-band alignment fixture with adjustable sidebar assembly in place.

spond to the two principal joints of the ankle complex, the ankle and subtalar joints. However, this external jointed structure is not automatically compatible with the normally occurring motions of the anatomic joints. Only when the brace joints are positioned so that their axes coincide with the axes of the respective anatomic joints will the external and anatomic structures move together without interference, as a single structure. When such an alignment is achieved and maintained, the ex-

ternal structure will be kinematically equivalent (analogous) to the anatomic structure, and corresponding elements of the two structures will move together without any relative motion. Only when it is so aligned is the external structure properly called an external mechanical analog of the ankle complex.

Relative motions between corresponding elements of the external and anatomic structures result when respective joint axes are not properly aligned. These relative motions give rise to restrictions of normal anatomic joint motions and to undesirable forces between the brace and the leg. It is the objective of alignment of the dual-axis brace to position the joint axes of the brace close enough to the respective anatomic joint axes that relative motions and unwanted forces between the two systems are reduced to negligible levels.

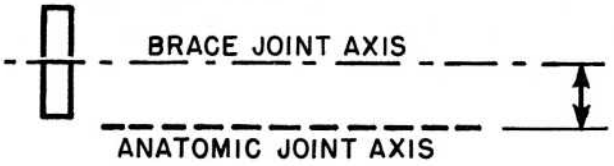
## THE ALIGNMENT PROCESS

The process of alignment consists of a systematic elimination of misalignment. Misalignments between respective external and anatomic joints are systematically reduced by adjustments to the brace based on observation and interpretation of discrepancies between the motions of the brace and the leg, such as pumping or tilting, or rotation of the cuff on the leg (see Tables 1 and 2 in Appendix III).

In general, misalignments between an anatomic joint axis and the corresponding brace-joint axis consist of two components, linear (parallel) misalignment and angular misalignment. Angular misalignment exists when corresponding axes are not parallel to each other (Fig. 20–A). Simple linear misalignment between two corresponding axes exists when the axes are parallel but separated from each other (Fig. 20–B) in some direction perpendicular to both axes. Linear misalignment may also exist without the axes being parallel, however, when both linear and angular misalignments occur simultaneously. In that case the two components of misalignment are simply superimposed (Fig. 20–C). Although the two components are almost always observed in combination, the alignment process is simplified and made more systematic when they are dealt with separately. Characteristically, linear misalignments give rise to pumping and tilting of the cuff on the leg while angular misalignments cause rotations of the cuff on the leg as well as other rotatory discrepancies.

The process of alignment is complicated by the close interrelation between the ankle and subtalar joint axes and the difficulty of observing movements of the talus. These two joints normally function together, much like the two joints which make up the familiar Hooke's (universal) joint, and it is difficult to determine which part of a motion occurs

a. Angular Misalignment




b. Linear (Parallel) Misalignment

c. Combined Angular and Linear Misalignment

FIGURE 20.—Misalignment between two joint axes.

at one joint and which part at the other. Furthermore, it is not practical to attach any instrument or device directly to the talus in order to permit the ankle and subtalar joints to be dealt with individually. Because of the interaction between the two anatomic joints, misalignment of one of the brace joints can interfere with the process of aligning the other by producing spurious indications of misalignment (compare Tables 1 and 2). Fortunately, if the misalignment of one brace joint is slight, its effect on alignment of the other joint will be small, even if both joints are moving simultaneously.

## PRELIMINARY AND DYNAMIC ALIGNMENT

In practice the alignment process consists of two parts: preliminary alignment and dynamic alignment. (More complete details of these procedures will be found in Appendix III; an alternate procedure is described in a report specifically concerned with fabrication and alignment (*6*).) The purpose of the preliminary alignment is to attach the adjustable brace to the patient's shoe and to prealign respective brace joints and anatomic joints as accurately as possible by noting anatomic landmarks. This static prealignment simplifies the subsequent dynamic alignment because it reduces the effects of interaction between the subtalar and the ankle joints.

During the dynamic alignment, the alignment of respective joints is further refined on the basis of observed relative motion between the brace and the leg. The dynamic alignment process consists of actively or passively moving the subtalar or ankle joint and noting what relative motion between the brace and the leg, if any, results from such movement. Upon reference to Table 1 for the ankle joint, or Table 2 for the subtalar joint, the significance of the observed relative motion can be determined and an appropriate adjustment of the position of the corresponding brace joint made. This process is repeated, adjusting the position of first one joint and then the other, until no relative motions of the brace on the leg are observed when the foot is moved relative to the leg about either or both of the two joints. The alignment process is then complete. Fabrication of the final brace entails individual duplication of the three main elements of the adjustable brace—stirrup, yoke, and sidebar—and assembly of the fabricated parts as described above.

## THE PERMANENT RECORD

It is desirable to be able to keep a permanent record of a particular patient's brace configuration in order to permit rapid repair or refabrication of damaged brace parts and to provide a quantitative measure of changes which may occur as a result of growth or of improvement or deterioration of the patient's condition.

A combination of graphic and numerical descriptions of the dual-axis brace can be used to provide such a permanent record. Details of the procedure are given in Appendix IV.

## REFERENCES

1. Henderson, W. H. and L. W. Lamoreux: The Orthotic Prescription Derived from a Concept of Basic Orthotic Functions. Biomechanics Laboratory, University of California, San Francisco and Berkeley. Technical Memorandum. San Francisco, The Laboratory, Oct. 1966. 12 pp.

2. DESAI, S. M. and W. H. HENDERSON: Engineering Design of an Orthopedic Brace. Biomechanics Laboratory, University of California, San Francisco and Berkeley, Technical Report 45. San Francisco, The Laboratory, Oct. 1961. 44 pp.
3. ISMAN, R. E. and V. T. INMAN: Anthropometric Studies of the Human Foot and Ankle. Biomechanics Laboratory, University of California, San Francisco and Berkeley, Technical Report 58, San Francisco, The Laboratory, May 1968. 33 pp. (Reprinted in this issue of the Bulletin.)
4. HICKS, J. H.: The Mechanics of the Foot. I. The Joints. J. Anat., 87: 345–357, Oct. 1953.
5. MANTER, J. T.: Movements of the Subtalar and Transverse Tarsal Joints. Anat. Rec., 80: 397–410, Aug. 1941.
6. CAMPBELL, J. W., W. H. HENDERSON, and D. E. PATRICK: UC-BL Dual-Axis Ankle-Control System: Casting, Alignment, Fabrication, and Fitting. Biomechanics Laboratory, University of California, San Francisco and Berkeley, Tehcnical Report 60. San Francisco, The Laboratory, Jan. 1969. (Printed in this issue of the Bulletin.)

## Appendix I

## DESIGN OF BRACE COMPONENTS

One of the objectives of the dual-axis brace project was to improve and develop further the brace components. Listed below are several general areas of concern and specific goals to be achieved for the successful fulfillment of this objective.

*Desired control functions:* Toe-lift and eversion assists should be provided.

*Durability:* All parts, particularly the joints and the attachment to the shoe, should be designed for a service life in excess of 5 years.

*Precision:* Joints should provide the appropriate motion (rotation) with little or no free play except in the plane of rotation.

*Convenience and comfort for the wearer:* Goals are interchangeability between shoes, attractive appearance, minimal required maintenance, minimal weight, and lack of annoying pressures.

*Ease of fabrication:* Technique should be simple and possibilities for improper assembly should be eliminated.

*Low cost:* The device should be simple to manufacture and be made of economical materials to keep the cost of parts down; ease of fabrication will help to keep labor costs low.

The components of the brace and their chronological development will be discussed element by element, starting with the attachment to the shoe and progressing upward to the attachment to the leg.

### Channel and Stirrup

The external equivalent ("analog") of the subtalar joint is called the *heel joint* (Fig. 9). The element of the heel joint which attaches to the shoe is called the *stirrup*. In the earliest braces the stirrup was perma-

nently attached to the shoe (Fig. 21), but in subsequent models an intermediate part, the *channel,* was permanently mounted in the shoe and the stirrup slipped into the channel. This arrangement makes it possible to remove the stirrup when desired, so that a single brace can be used on several shoes.

Early channels were made of $\frac{3}{16}$-in.-thick stainless steel flat stock with a simple shallow slot ($\frac{1}{8}$ in. deep by $\frac{1}{2}$ in. wide) milled along one surface (Fig. 22). The channel was permanently attached to the underside of the shoe, and the tang of the stirrup was simply inserted into the space between the channel and the shoe. Wear of the steel channel was not a problem, but external loads on the brace which tended to twist the tang of the stirrup within the channel caused the edges of the tang to cut into the material of the shoe, so that undesirable looseness occasionally resulted. To improve the security of the coupling between stirrup and channel the simple slot of the early design was replaced with a shallow T-slot. This change necessitated the extra manufacturing step of milling the tang of the stirrup to fit into the T-slot, but the result was an inherently stronger coupling. The material of the channel also was changed to an aluminum alloy in order to simplify machining and reduce weight. With the T-slot, the open side of the channel can be placed away from the underside of the shoe instead of toward it; this arrangement permits simple alignment of the retaining screw holes which must be drilled in the shoes when a single brace is to

FIGURE 21.—Early brace, showing dual-row ball-bearing heel joint, yoke with circular cross section, and permanently mounted stirrup.

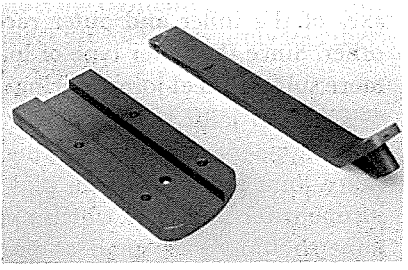


FIGURE 22.—Early channel and stirrup.

be used on several shoes. The widths of the stirrup tang and of the channel were subsequently increased (Fig. 7 and 8) to increase durability and simplify manufacture of the parts.

Other materials, including plastics, were considered, and one channel of Delrin was made and tested. Although this channel subsequently became fractured, it eliminated problems of corrosion and made the stirrup much easier to remove from the channel after extended use. Further consideration of plastic or reinforced plastic materials is recommended in any future refinement of the brace design.

Upon final assembly, the tang of the stirrup is lubricated with silicone grease to protect against corrosion and is inserted into the channel. The stirrup is locked in place by a retaining screw which is inserted from inside the shoe and passes through both the channel and the stirrup, preventing the stirrup from being withdrawn.

### Heel Joint

The heel joint couples the yoke to the stirrup and is the external equivalent ("analog") of the anatomic subtalar joint. In the early braces this joint consisted of a double-row ball bearing which was smooth in action and durable but rather large (see Fig. 21). To reduce the bulk of the heel joint and simplify its fabrication, a single ball bearing was substituted for the double one. Unfortunately, this single-row bearing was not adequately durable in service.

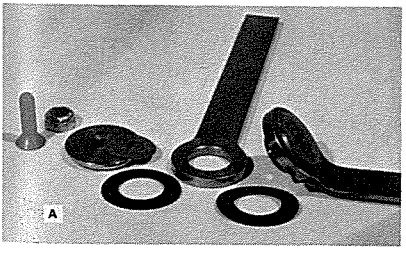
The construction of the brace is such that the toe-lift moment, which is applied by a spring at the analog ankle joint (*sidebar joint*), must be transmitted through the heel joint to the stirrup and then to the channel and shoe. While the radial loads on the heel joint are normally quite small, this toe-lift moment which the heel joint must withstand and transmit is on the order of 15 in.-lb. (in an adult brace). Conventional single-row ball bearings are well suited to supporting radial loads but poorly suited to withstanding bending moments which tend to force the axes of the inner and outer races out of parallel alignment with each other. Since the latter type of loading is encountered in the heel joint, a more suitable heel-joint bearing was sought.

The heel joint must rotate freely, but to achieve and maintain accurate alignment of the axes of the anatomic and analog subtalar joints, the brace joint must be free of play or looseness and should provide an adjustment for any wear which might occur during use. Furthermore, the joint should be as small as possible, particularly in thickness, and it must be unaffected by a dusty or muddy environment.

In the first joint designed to satisfy these revised requirements, a short cylindrical bearing pin, ½ in. in diameter, was permanently attached to the stirrup, and the end of the *yoke* (the coupling link which connects

heel joint to sidebar joint) was designed to fit around the pin (Fig. 23). The joint was closed by securely clamping a flanged cap onto the end of the pin. With this arrangement the yoke was retained between two flanges (the faces of the stirrup and the cap) which were rigidly attached to each other. Clearance was adjusted by placing small shim washers between the end of the pin and the cap (*not* by loosening the screw which clamped the cap to the pin). This method of adjustment was used because the rigid connection between cap and pin permitted the cap to assist more effectively in withstanding the toe-lift moment. Two washers, 0.010 in. thick and made of sheet plastic bearing material, were used in the assembled joint as thrust bearings. The most satisfactory bearing material subsequently proved to be a woven glass-fiber fabric impregnated with Teflon.

The shim adjustment for bearing clearance was inconvenient, and, once the durability of the design had been established, a simplified adjustment for clearance was incorporated by using an adjustable threaded coupling between the pin and the cap, or outer flange. Later, the pin and the cap were both provided with flanges, the rigid attachment to the stirrup was omitted, and a third bearing washer was placed between this inner flange and the stirrup, allowing the assembled pin with its two flanges to rotate freely within the assembled joint (see Fig. 9). The free rotation of the flanged pin contributed to a more uniform distribution of wear in the joint. The free pin configuration does have the disadvantage that it results in the center bearing washer being pinched at the edges more severely than the two outer washers when moments are applied to the joint, but in spite of this disadvantage, adequate bearing durability has been obtained with use of the reinforced Teflon bearing washers. The threaded coupling between the flanged screw and the flanged nut permits a simple and accurate adjustment of the bearing clearance. When this adjustment has been completed the flanged screw can be expanded against the flanged nut by tightening a concentric, tapered locking screw, so that the two flanges are locked securely together.



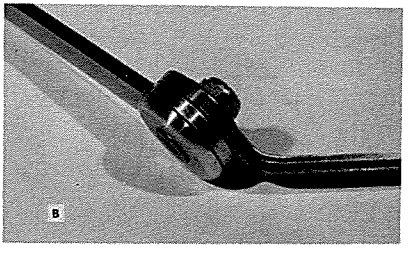




FIGURE 23.—Original heel joint with plastic bearings. *A*, parts; *B*, assembled.

This method of locking the heel joint clearance adjustment has been very effective, but the expanding inner thread is undesirably complex to manufacture. A simpler way of locking the inner and outer flanges together has been sought and sample parts with nylon locking inserts have been obtained (Fig. 24). A single insert is not satisfactory because it forces the two flanges out of parallel alignment with each other. Samples with three equally spaced inserts are under test.

For the heel joint to rotate freely but without free play, the joint surfaces must be flat and parallel within close tolerances. The flanges of the pin must be parallel to each other, and the ends of the stirrup and the yoke, which are joined at the heel joint, must be flat and uniform in thickness. The first requirement has been satisfied by machining the flange and the coupling thread of each half of the pin in the same lathe setup to insure concentricity. The second has been satisfied by performing a final spot-facing operation on each side of each stirrup and yoke. For the spot-facing operation, a simple mild steel backup pad which accepts the pilot on the spot-facing tool is mounted in the tailstock of the lathe and the tool is held in a chuck in the spindle. A light cut is first taken off the face of the backup pad to insure that it is true, and then each stirrup and yoke is lightly faced off on each side in turn; the feed in the tailstock is used to control the depth of cut while the tang of the stirrup or yoke is supported on the lathe toolholder. For good results it is important that the support be horizontal and in the plane of the surface being machined, neither sloping nor displaced toward the headstock or tailstock of the lathe.

## Yoke

The function of the yoke is to maintain correct alignment between the analog subtalar joint (*heel joint*) and the analog ankle joint (*side-*

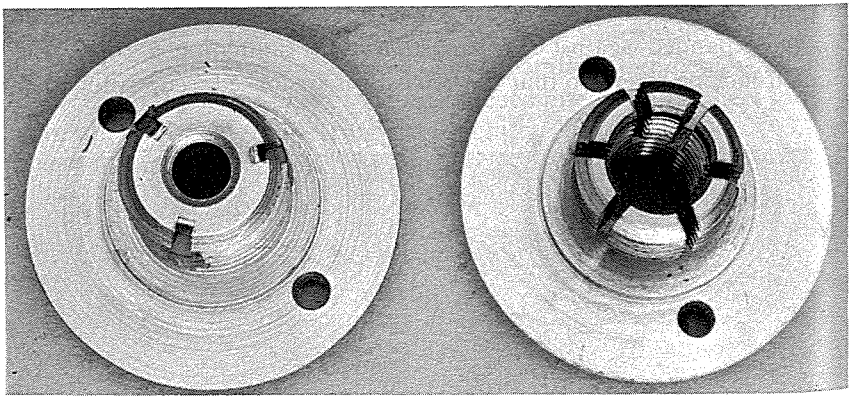


FIGURE 24.—Heel joint adjustment locks. *Left,* nylon inserts; *right,* expanding thread.

*bar joint*) (see Fig. 6). Thus, the posterior, or lower, end of the yoke is part of the heel joint and the anterior, or upper, end is part of the sidebar joint. In the early braces, the coupling of these two joints was accomplished with a ¼-in.-diameter steel rod which proved to be awkward to bend to the desired shape (Fig. 21). Consequently, with the redesign of the heel joint a new yoke was designed of ⅛-in.-thick austenitic stainless-steel flat stock (see Fig. 10). The flat-stock yoke is readily shaped with bending irons.

That part of the completed yoke assembly which mates with the sidebar joint is called the *sidebar joint tongue*; it is brazed to the tang of the yoke during fabrication of the brace.

### Sidebar Joint Tongue

A commercial toe-lift sidebar has been selected which has a clevis-type joint designed to mate with the stirrup of a conventional, single-axis ankle brace as shown in Figures 1 and 25-A. When the sidebar is used in the dual-axis brace, the joint mates with the sidebar-joint tongue on the upper end of the yoke. A compression spring which is built into the sidebar acts against a shoulder on the tongue to provide a toe-lift moment about the ankle joint.

The early sidebar joint tongues were constructed to permit adjustment (by regrinding the shoulder on the tongue) of the angular position of the joint at which the toe-lift spring began to function (Fig. 25-B). Later, it was found that little variation in this toe-lift starting position was required and a simpler tongue was designed which, in addition, permitted a somewhat greater degree of plantar flexion (Fig. 25-C). Unfortunately, this second model did not make full use of the bearing area available in the clevis joint and also tended to force the spring follower against the posterior side of its passage rather than directly against the toe-lift spring. Both of these factors contributed to rapid wear and high friction in the joint. The final form of the sidebar joint tongue is shown in Figure 25-D.

### Sidebar

The commercial sidebar is well designed and fabricated and neatly packages the toe-lift spring, but there is no convenient provision for adjusting the clearance of the joint in the event of wear or if the tongue is too thick or too thin. This lack of adjustability is not generally a problem in braces with double sidebars but can present a problem in the single-sidebar brace when it is desirable to achieve and maintain an accurate joint alignment. It may eventually become necessary to design a

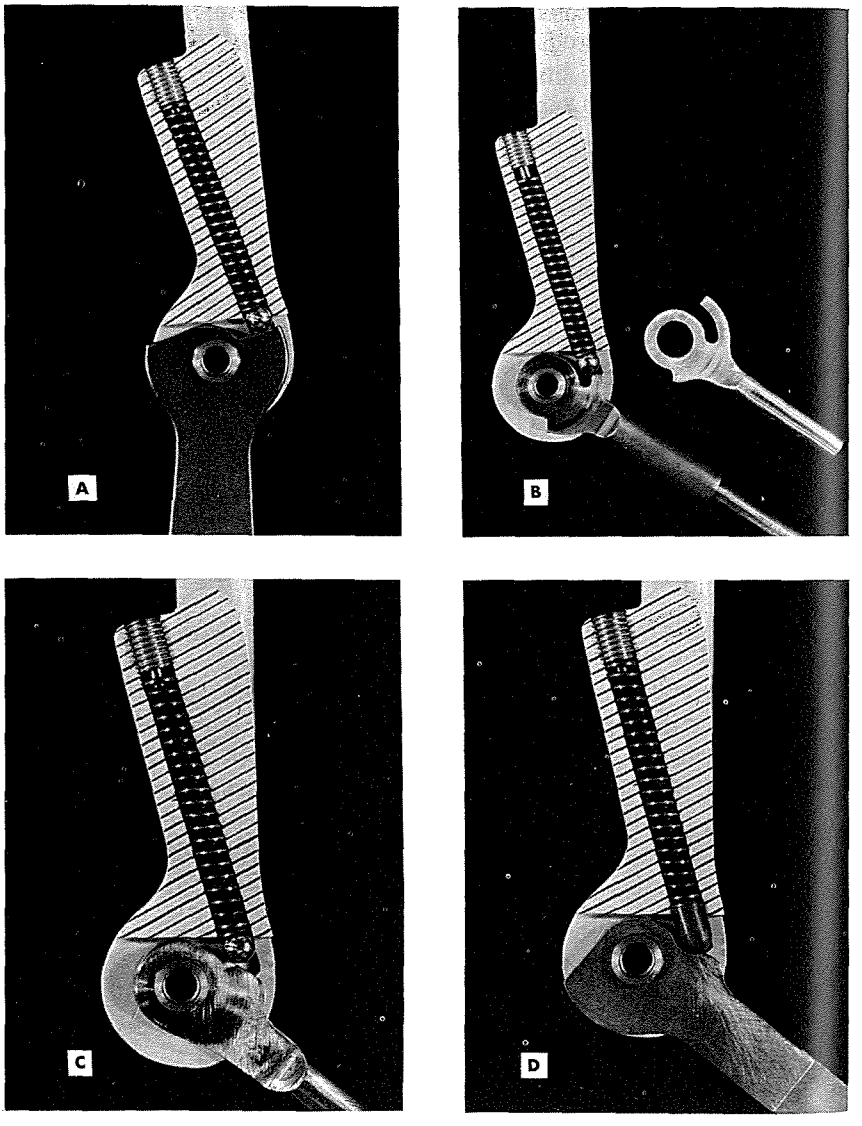



FIGURE 25.—Cutaway views of conventional sidebar. *A*, conventional stirrup; *B*, early sidebar joint tongue; *C*, intermediate sidebar joint tongue; *D*, current sidebar joint tongue with Nylatron spring follower.

sidebar joint which incorporates a clearance adjustment such as the one used in the heel joint.

Contained within the commercial sidebar is a coil spring which forces a steel ball against a shoulder on the sidebar joint tongue (Fig. 25-A,

25-B, 25-C), to provide the desired toe-lift moment. A cylindrical plug of Nylatron with a hemispherical distal end (Fig. 25-D and 26) was substituted for this steel ball; the result was a decrease in noise, friction, and wear of the sidebar joint tongue. The cylindrical plug also closes the distal end of the spring chamber more effectively than does the ball, thereby helping to keep lubricant in and foreign matter out of the chamber.

## Appendix II

### THE ADJUSTABLE BRACE AND BRACE FABRICATION EQUIPMENT

Two of the objectives of the dual-axis brace project were to develop a practical technique for locating the axes of the anatomic ankle and subtalar joints, and to develop reliable methods and equipment for fabricating a finished brace with its joint axes aligned to these anatomic joint axes. The decision was made to use an adjustable brace to accomplish the alignment; thus, the design objectives became (1) to design an alignment instrument consisting of a dual-axis brace, each element of which could be adjusted, or changed in shape, to permit the brace joints to be aligned with the respective anatomic joints and (2) to design appropriate fabrication fixtures which would insure an accurate

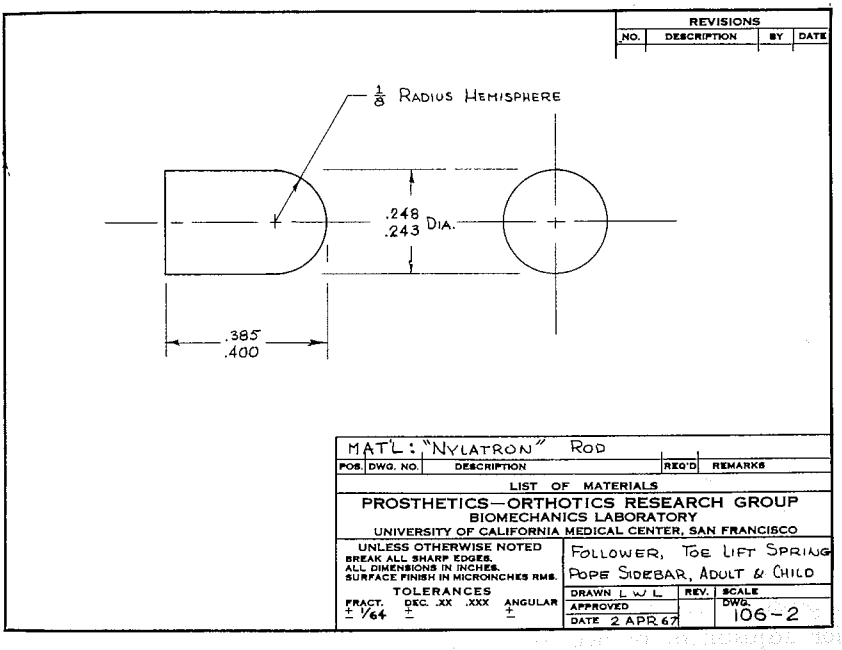



FIGURE 26.—Drawing of Nylatron toe-lift spring follower.

transfer of alignment from the adjustable brace to the final brace which is delivered to the patient. Listed below are several considerations which are relevant to the design of the adjustable brace and the fabrication quipment:

1. The adjustable brace must be kinematically and functionally equivalent to the dual-axis brace described in Appendix I.
2. The adjustments provided in the adjustable brace should be planned to make the alignment procedure as simple as possible.
3. The operation of the fabrication fixtures for alignment duplication should be made as simple as possible, with attention to the exclusion of possibilities for improper fabrication or assembly.

The elements of the adjustable brace and respective elements of the alignment duplication system will be discussed together, starting with the most distal elements.

### Adjustable Stirrup Assembly and Stirrup Bender

The chosen design of the brace (see Fig. 6) requires that the stirrup be bent during the process of fabrication so that the heel-joint surfaces are at an appropriate angle to the tang. The "appropriate" angle is determined by measurement of the bend angle of the adjustable stirrup assembly (see Fig. 13) after the adjustable brace (see Fig. 12) has been fitted to the patient.

A compact fit of the heel joint against the shoe requires a rather sharp bend in the stirrup; proper function of the heel joint, as well as proper fit of the stirrup tang into the channel, demand that the heel-joint surfaces and the tang not be bent or otherwise deformed during the bending of the stirrup. To satisfy all these requirements a stirrup bender (see Fig. 17) was designed and built which permits accurate control of the bending operation. The design of the stirrup bender dictated the configuration of the adjustable stirrup, for the two must be kinematically equivalent if the bender is to reproduce accurately all possible "bend" angles of the adjustable stirrup. This equivalence was obtained by placing the axis of the rotary joint, which permits adjustment of the stirrup "bend angle," in the adjustable stirrup in the same position relative to the heel-joint surfaces as the axis of the dowel pin over which the stirrup is bent in the bending fixture. In addition to the adjustable bend angle, an adjustment is provided which permits the adjustable stirrup to be translated medially or laterally and rotated internally or externally relative to the shoe.

To achieve the best possible cosmesis, the heel joint is placed as close as possible to the back of the shoe. As a result, there is no anteroposterior adjustment of heel-joint position. Furthermore, it has not been found necessary to provide for vertical adjustments of the heel-joint po-

sition. These adjustments were eliminated in a compromise between accuracy of adjustment and simplicity of the finished brace.

The base plate of the adjustable stirrup assembly is attached to the patient's shoe with heel nails, in place of the original heel, and the adjustable stirrup is simply clamped between this base plate and the heel plate by a single, central cap screw (see Fig. 14). For ease of adjustment during fitting it would be more satisfactory if separate locks were provided for linear and angular adjustments. After alignment of the adjustable brace and before the adjustable stirrup assembly is removed from the patient's shoe, the center line of the adjustable stirrup is marked on the underside of the shoe. During the final fabrication the channel is simply centered over this line and permanently attached to the shoe.

### Adjustable Yoke and Yoke Duplication Fixture

The function of the yoke is to maintain the heel joint and the sidebar joint in proper relationship to each other (see Fig. 6). For true analog alignment the axes of these two joints should not intersect because the axis of the anatomic subtalar joint generally passes somewhat below that of the ankle joint,[c, d, e] and the respective joints of the external analog should have the same spatial relationship. Hence, the function of the yoke can be described as that of connecting to each other two joints with skew axes. It is a property of any two skew (i.e., nonintersecting and nonparallel) axes that they have a unique mutual perpendicular (Fig. 27). The length of this straight-line segment, which is perpendicular to both axes, is the minimum distance between the two axes; no shorter line connecting the two axes exists. For purposes of numerically defining a yoke configuration, i.e., defining the relationship between the heel and sidebar joints, the length of the mutual perpendicular (length $L$ in Fig. 27 and 28) provides an excellent starting point.

A second logical parameter for defining the yoke configuration is the angle which is observed between the two axes when they are viewed along the mutual perpendicular (angle $A$ in Fig. 27 and 28). These two parameters are sufficient to define the relationship between the axes of the two joints of the yoke. To describe completely the locations of the joint members themselves, we need only note, in addition, the distance of the face of each joint from the mutual perpendicular (dimensions $D_1$ and $D_2$ in Fig. 28).

---

[c] Isman, R. E., and Inman, V. T.: Anthropometric Studies of the Human Foot and Ankle. Biomechanics Laboratory, University of California, San Francisco and Berkeley. Technical Report 58. San Francisco, The Laboratory, May 1968. 33 pp. (Reprinted in this issue of the Bulletin.)

[d] Hicks, J. H.: The Mechanics of the Foot. I. The Joints. J. Anat., 87: 345–357, Oct. 1953.

[e] Manter, J. T.: Movements of the Subtalar and Transverse Tarsal Joints. Anat. Rec., 80: 397–410, Aug. 1941.

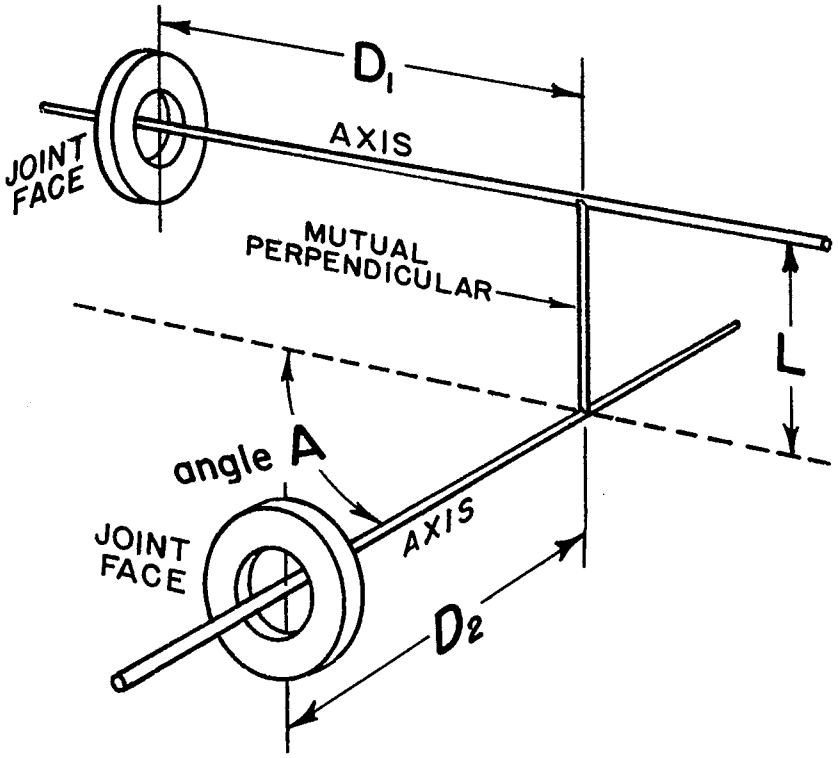



FIGURE 27.—Parameters defining relationship between two joints with skew axes.

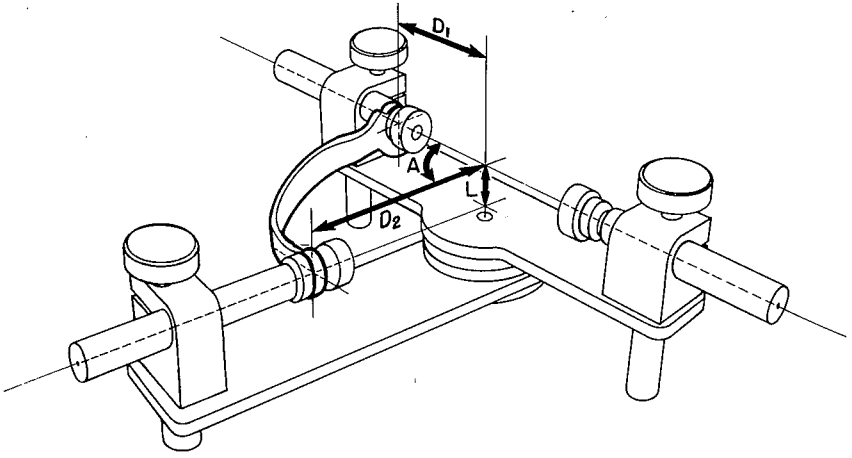



FIGURE 28.—Yoke duplication fixture and completed yoke, showing relationships between heel and sidebar joints.

Each of the four parameters described above can be adjusted on the adjustable yoke, though not entirely independently (Fig. 12 and 15). The first parameter—the shortest distance between the two joint axes—is independently adjustable and will remain constant during other adjustments. The other three parameters have been made interdependent in order to simplify adjustments during the alignment procedure and permit a more compact design. Experience with fitting the brace has shown that, for short leg braces, the distance between the two axes is of little practical importance. Considerable simplification of the alignment and fabrication procedures and equipment results from arbitrarily assuming this distance to be zero.

The construction of the yoke duplication fixture permits individual adjustment of each of the four parameters described above (see Fig. 18). After fitting of the adjustable brace to the patient, the three main elements of the brace are separated from each other and the adjustable yoke is placed in the yoke duplication fixture. The fixture is adjusted to mate with the joints of the adjustable yoke, and all adjustments of the fixture are locked. The adjustable yoke is then removed and the yoke for the finished brace is fabricated directly in the fixture by appropriately bending the yoke and brazing it to the sidebar joint tongue. During the bending and brazing operations, the two joints are maintained in proper alignment with each other by the fixture. A permanent record of the yoke dimensions can then be obtained by simply measuring the four parameters on the fixture and recording them.

### Adjustable Sidebar and Calf-Band Alignment Fixture

The purpose of the sidebar is to maintain the calf band in the correct relationship to the sidebar joint and vice versa (see Fig. 6). In the adjustable brace the sidebar is so constructed that the sidebar joint can be positioned as desired and then locked in place (see Fig. 12 and 16). A locking ball-and-socket joint connects the sidebar to the calf band.

The calf-band alignment fixture serves the same function relative to the sidebar and calf-band assembly that the yoke duplication fixture does to the yoke (see Fig. 19). After alignment of the adjustable brace to the patient, the adjustable sidebar and calf-band assembly is placed in the alignment transfer fixture. This fixture holds the calf band fixed relative to the sidebar joint so that the adjustable sidebar can be removed without loss of alignment between the calf band and the sidebar joint. A standard sidebar is then shaped to a tracing of the patient's leg contour, fitted between the calf band and the sidebar joint tongue (which is built into the fixture), and permanently attached to the calf band.

## Appendix III

## ALIGNMENT OF THE DUAL-AXIS BRACE

The principles of alignment of the dual-axis brace are explained in the main body of the report. The purpose of this Appendix is to describe in greater detail the actual application of these principles. Additional instructions, which make use of somewhat different procedures for alignment and fabrication of the dual-axis brace, are to be found in the companion report.[f]

The objective of alignment of the dual-axis brace is to position the axes of the brace joints sufficiently close to the axes of the respective anatomic joints that no significant discrepancies between the motions of the brace and those of the leg can be detected by the wearer or by an observer. This is accomplished by having the patient wear a dual-axis adjustable brace (Appendix II) in which the brace joints can be moved into alignment with the respective anatomic joints. The direction in which the brace joints should be moved is determined by observing and interpreting, with the aid of Tables 1 and 2, the relative motions which occur between brace and leg when the foot is moved or when the patient walks. The criterion for alignment is based on detectability of discrepancies in motion between the brace and the leg; if no discrepancies can be detected by the patient or the fitter, then, for normal bracing purposes, the brace is well aligned.

For convenience, the alignment procedure is divided into two parts, preliminary, or bench, alignment and dynamic alignment. In the preliminary alignment the adjustable brace is placed on the patient and the brace joints are prepositioned with the aid of rules of thumb based on experience and with reference to anatomic landmarks. In the dynamic alignment process, alignment of the respective brace and anatomic joints is further refined by interpretation of relative motions, as mentioned above and described in detail in the discussion which follows. An accurate preliminary alignment simplifies the final dynamic alignment by making it easier to separate the effects of ankle-joint/sidebar-joint misalignment from those of subtalar-joint/heel-joint misalignment.

### Preliminary Alignment

The heel of the patient's shoe is removed and the base plate of the adjustable stirrup is attached in its place with heel nails. The adjustable stirrup and the clamping plate are then attached to the base plate

[f] Campbell, J. W., W. H. Henderson, and D. E. Patrick: UC-BL Dual-Axis Ankle-Control System: Casting, Alignment, Fabrication, and Fitting. Biomechanics Laboratory, University of California, San Francisco and Berkeley, Technical Report 60. San Francisco, The Laboratory, Jan. 1969. (Printed in this issue of the Bulletin.)

by means of the central clamp screw. The adjustable stirrup is locked in place with the heel joint internally rotated approximately 15 deg. from the long axis of the shoe. An aluminum alloy calf band is bent to match the contour of the patient's leg and is attached to the ball joint of the adjustable sidebar assembly with a single cap screw.

The stirrup and sidebar are connected to each other with the adjustable yoke assembly by assembling the heel and sidebar joints. Assembly of these two joints completes the assembly of the adjustable brace on the patient's shoe, and the patient can then put his shoe back on. The orthotist completes the preliminary alignment by positioning the sidebar joint so that the joint axis passes approximately through the extreme distal tips (not the extreme medial and lateral points) of the medial and lateral malleoli. The 15 deg. internal rotation of the heel joint and the alignment of the sidebar-joint axis with the distal tips of the malleoli will usually bring the axes of the two brace joints quite close to the axes of the corresponding anatomic joints, thereby minimizing the adjustments that must be made during the dynamic alignment.

## Dynamic Alignment

Linear misalignments between corresponding anatomic and brace joints are more readily detected than angular misalignments. It is therefore most convenient to begin the dynamic alignment with the elimination of the linear component of misalignment and then proceed to the elimination of the angular component. Throughout this discussion it is assumed that the shoe fits well and does not move appreciably relative to the foot. If for some reason this is not the case, it will be necessary to correct any problems of shoe fit before proceeding with the alignment of the dual-axis brace.

Beginning with the ankle/sidebar-joint pair, the foot is moved, either actively or passively, about the ankle joint while motion about the subtalar joint is minimized. If there exists a linear component of misalignment between the axis of the sidebar joint and the axis of the ankle joint, the movements of the foot will be accompanied by proximodistal "pumping" of the calf band and/or anteroposterior swinging of the sidebar relative to the leg, as outlined in Table 1. By reference to Table 1, the cause of the relative motion can be determined and appropriate corrective adjustments of the sidebar-joint position made. This process is repeated until the relative motions (pumping and swinging) are eliminated.

After elimination of the linear component of misalignment between the ankle and sidebar joints, attention is shifted to the subtalar-joint/heel-joint pair. The foot is again moved actively or passively, this time about the subtalar joint, with minimum movements about the ankle

joint. If the misalignment of the heel joint is such that the axis is displaced medially or laterally from the subtalar-joint axis, proximodistal pumping of the calf band on the leg will accompany movements of the foot about the subtalar joint; similarly, proximal or distal displacements of the heel-joint axis relative to the subtalar-joint axis will give rise to mediolateral swinging of the sidebar, toward and away from the lateral malleolus. Observation of these relative motions and reference to Table 2 will make it possible to ascertain the nature of the misalignment. Appropriate adjustments of the adjustable brace can then be made. When the position of the heel joint is changed, it is important not to alter the position of the sidebar joint. This adjustment process is repeated until the relative motions, pumping of the cuff and swinging of the sidebar, are no longer observed.

At this point, the linear component of misalignment has been eliminated between both pairs of joints. The angular components of misalignment are dealt with next. The foot is again moved about the ankle joint. At this time there should be no indications of linear misalignment but there usually will be relative motions of a rotatory nature between brace and leg, indicating angular misalignment, as described in Table 1. By observation of these relative motions and referral to Table 1 the nature of the misalignment can be ascertained and appropriate adjustments of the sidebar-joint position can be made. This process is repeated until all indications of misalignments between ankle and sidebar joints have been eliminated.

This angular alignment procedure is repeated for the subtalar/heel-joint pair, with reference to Table 2. The alignment process is then completed by making a final recheck of linear alignment at each joint pair, in order to correct any small linear misalignments that may have inadvertently occurred during the course of the adjustments made for the angular alignment.

The information in Tables 1 and 2 was obtained by analyzing the combined kinematic system of leg, foot, shoe, and brace with the aid of simplified sketches (Fig. 29–33).

### Schematic Notations

All views are of the lateral side of the leg (Fig. 29).

Definitions: By plantar flexion and dorsiflexion are meant the motions which take place about the ankle joint. By inversion and eversion are meant the motions which take place about the subtalar joint.

### Linear Misalignments

Anteroposterior misalignment of the ankle-joint/sidebar-joint pair: Consider the case when the sidebar joint is anterior to the ankle joint (Fig. 30).

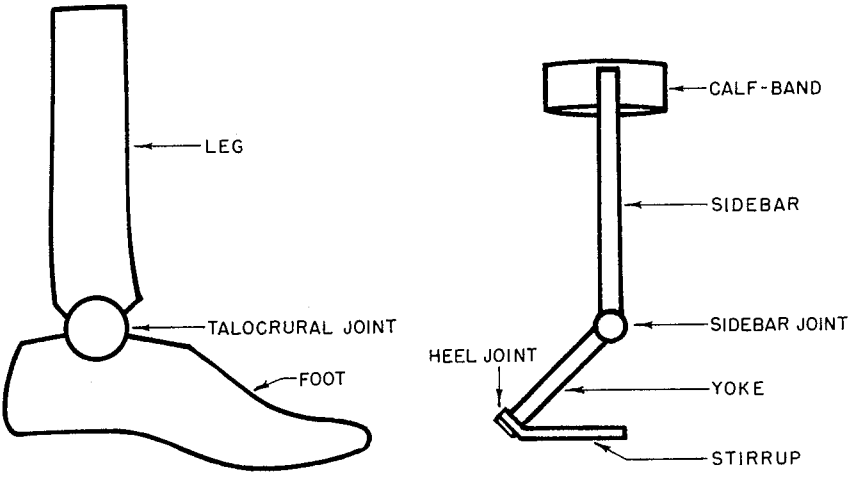



FIGURE 29.—Simplified sketches of related anatomic and brace structures, showing structures used in analysis of misalignment.

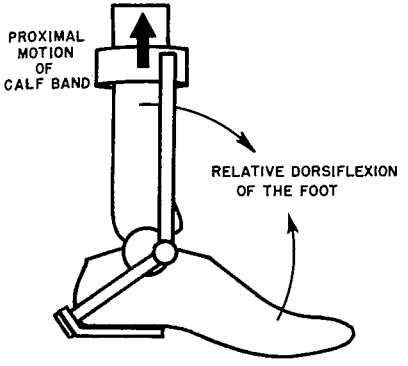



FIGURE 30.—Linear misalignment: anterior displacement of sidebar-joint axis relative to ankle-joint axis.

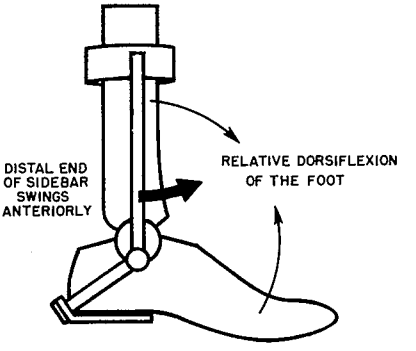



FIGURE 31.—Linear misalignment: distal displacement of sidebar-joint axis relative to ankle-joint axis.

Relative dorsiflexion of the foot will cause the calf band to move proximally on the leg.

Plantar flexion will cause the calf band to move distally. If the sidebar joint is positioned posterior to the ankle joint, the motions of the calf band will simply be reversed in direction (Rule 1, Table 1).

Mediolateral misalignment of the subtalar-joint/heel-joint pair: The effects of mediolateral misalignment of the heel joint relative to the subtalar joint can be analyzed in exactly the same manner used above, yielding the first rule of Table 2.

Proximodistal misalignment of the ankle-joint/sidebar-joint pair:

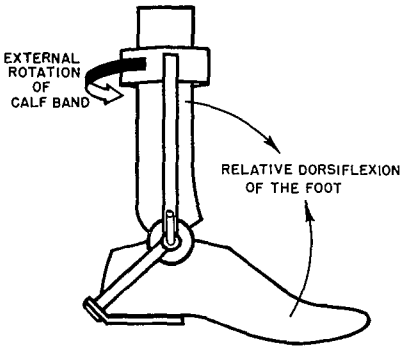



FIGURE 32.—Angular misalignment: lateral end of sidebar-joint axis proximal and medial end distal to ankle-joint axis.

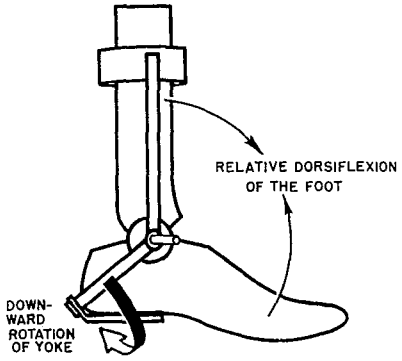



FIGURE 33.—Angular misalignment: internal rotation of sidebar-joint axis relative to ankle-joint axis.

Consider the case when the sidebar joint is distal to the ankle joint (Fig. 31).

Relative dorsiflexion of the foot will cause the distal end of the sidebar to swing in an anterior direction relative to the leg. Plantar flexion will cause the sidebar to swing in a posterior direction. If the sidebar joint is positioned proximal to the ankle joint, the motions of the sidebar will be reversed in direction (Rule 2, Table 1).

Proximodistal misalignment of the subtalar-joint/heel-joint pair: The effects of proximodistal linear misalignment of the heel joint relative to the subtalar joint can be analyzed in exactly the same manner, yielding the second rule of Table 2.

## Angular Misalignments

Angular misalignment of the ankle-joint/sidebar-joint pair in a vertical plane: Consider the case when the sidebar-joint axis is inclined with the lateral end proximal to, and the medial end distal to, the ankle-joint axis (Fig. 32).

During relative dorsiflexion of the foot the medial side of the calf band moves farther than the lateral side because it is farther from the inclined sidebar-joint axis. As a result, the most notable relative motion between the leg and the brace is a relative external rotation of the calf band on the leg. Plantar flexion will give rise to a relative internal rotation. Misalignment of the axes such that the lateral end of the sidebar-joint axis is distal to, and the medial end proximal to, the ankle axis will give rise to relative rotations in directions opposite to those stated (Rule 3, Table 1).

Angular misalignment of the subtalar-joint/heel-joint pair in a verti-

TABLE 1.—*Principal Indications of Misalignment Between Sidebar Joint and Ankle Joint, Listed in Order of Importance*

(The relative motions listed will accompany plantar flexion of the foot. Dorsiflexion will cause opposite motions. Avoid moving the subtalar joint.)

| Relative motion observed during plantar flexion | Misalignment |
|---|---|
| | *Linear (Parallel)* |
| 1. Proximal (distal) movement of cuff on leg. | Sidebar-joint axis posterior (anterior) to ankle-joint axis. |
| 2. Anterior (posterior) swing of sidebar past lateral malleolus. | Sidebar-joint axis proximal (distal) to ankle-joint axis. |
| | *Angular* |
| 3. Internal (external) rotation of cuff on leg. | Sidebar-joint axis inclined to the ankle-joint axis in a vertical plane; lateral end too far proximal (distal) and medial end too far distal (proximal). |
| 4. Nonanalogous[a] upward (downward) rotation of the yoke about the heel-joint axis. | Sidebar-joint axis internally (externally) rotated relative to ankle-joint axis. |

[a] A nonanalogous motion is one which occurs at a brace joint without simultaneously occurring at the analogous anatomic joint.

cal plane: The effects of the heel-joint axis being more, or less, steeply inclined than the subtalar-joint axis can be analyzed in the manner described in the preceding paragraph, yielding the third rule of Table 2.

Angular misalignment of the sidebar-joint/ankle-joint pair in a horizontal plane: Consider the case when the sidebar-joint axis is internally rotated relative to the ankle-joint axis (Fig. 33).

During relative dorsiflexion of the foot the leg rotates directly forward (relative to the foot) about the ankle-joint axis. If no rotation were allowed at the heel joint, the sidebar and calf band would tend to deviate medially as they rotated forward about the sidebar joint. Such deviation is not possible, however, because the calf band is attached to the leg. The result is that dorsiflexion is accompanied by a "nonanalogous" rotation of the heel joint, i.e., a rotation of the heel joint which does not correspond to any rotation of the subtalar joint. This rotation is a relative eversion and is observed as a downward rotation of the yoke about the heel-joint axis. Plantar flexion would be accompanied by

TABLE 2.—*Principal Indications of Misalignment Between Heel Joint and Subtalar Joint, Listed in Order of Importance*

(The relative motions listed will accompany inversion of the foot. Eversion will cause opposite motions. Avoid moving the ankle joint.)

| Relative motion observed during inversion | Misalignment |
|---|---|
| | *Linear* |
| 1. Proximal (distal) movement of cuff on leg. | Heel-joint axis medial (lateral) to subtalar-joint axis. |
| 2. Movement of sidebar toward (away from) lateral malleolus. | Heel-joint axis distal (proximal) to subtalar-joint axis. |
| | *Angular* |
| 3. Internal (external) rotation of cuff on leg. | Heel-joint axis inclined less (more) steeply than subtalar-joint axis. |
| 4. Nonanalogous[a] dorsiflexion (plantar flexion) of sidebar joint. | Heel-joint axis internally (externally) rotated relative to subtalar-joint axis. |

[a] A nonanalogous motion is one which occurs at a brace joint without simultaneously occurring at the analogous anatomic joint.

a nonanalogous upward rotation of the yoke. If the sidebar-joint axis were externally rotated relative to the ankle-joint axis, the resulting nonanalogous rotations at the heel joint would be in directions opposite to those described (Rule 4, Table 1). Note that in the conventional single-axis ankle brace there is no heel joint to accommodate these relative motions and they must be absorbed by the subtalar joint.

Angular misalignment of the subtalar joint/heel joint in a horizontal plane: The effects of internal or external rotation of the heel-joint axis relative to the subtalar-joint axis can be analyzed in the manner described in the paragraph above, resulting in the fourth rule of Table 2.

## Appendix IV

### PERMANENT RECORD

One of the objectives of the design of the dual-axis brace was to provide a method for permanently recording the configuration of a given brace. The existence of an accurate method for numerically or graphically describing the configuration of a patient's brace would make it possible to keep a meaningful permanent record of the patient's history

and progress, and would permit the refabrication of damaged brace parts without the necessity for a complete refitting. Some of the possibilities for a record of this sort were mentioned in the main body of the report. These will be summarized and expanded here.

### Channel

The location of the channel (see Fig. 7) on the shoe is recorded most simply by making a paper pattern of the shoe sole and marking the channel center line on this pattern. Such a pattern permits accurate placement of a channel on a new shoe if the new shoe is built on the same last as the original. If a shoe built on a different last is to be used, the pattern may provide enough information to permit a reasonably accurate fitting of the channel, but, in general, changes in shoe style or size can be expected to require a refitting by means of the adjustable brace.

### Stirrup

The bend angle (see Fig. 13) is the only parameter that needs to be recorded for the stirrup (see Fig. 8). If this angle is known a new stirrup can be prepared quickly and easily with the stirrup bender (see Fig. 17).

### Yoke

The parameters which describe the shape of the yoke (see Fig. 10) were described in detail in Appendix II. They are: the shortest distance between the two joint axes (the length of the mutual perpendicular—length $L$ in Fig. 28), the angle between the two joint axes (when viewed along the mutual perpendicular—angle $A$ in Fig. 28), and the distance of each joint face from the mutual perpendicular ($D_1$ and $D_2$ in Fig. 28). All of these parameters can readily be measured on the yoke duplication fixture (Fig. 18) after the fabrication of the yoke.

### Calf Band and Sidebar Assembly

The contour of the sidebar (see Fig. 11) is readily recorded by tracing its outline on a piece of paper, but accurately recording the relationship between the sidebar joint and the calf band is not so simple. A numerical system for recording this relationship is certainly possible, but it is of questionable value because of its complexity. The lack of a complete record of the relationship between the calf band and the sidebar joint may occasionally require a refitting with use of the adjustable sidebar in conjunction with the patient's old channel, stirrup, yoke, and calf band. Combining the parts from the adjustable fitting brace and the patient's finished brace is possible whenever only a single element needs to be refitted, since the same joint construction is used in both the adjustable brace and the final brace which is fabricated for the patient.