Biomechanical Considerations in the Design of a Functional Long Leg Brace*

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Abstract

A fund of knowledge and experience exists in the field of biomechanics which should provide sufficient foundation for design of a lower extremity brace offering restoration of function for the paralyzed leg. This paper sets forth the rationale through which such a brace and its component parts were developed, and gives a brief explanation of the techniques required for its application.

Introduction

The two primary functions of the lower extremities are to support the weight of the body and to propel the body. If there is functional loss through paralysis, there are many ways of providing support and propulsion —the wheel chair for one example—but the average individual has a strong preference for those methods which most closely resemble normal locomotion. That is to say, he wants to continue to use his legs even though one or both may no longer be capable of support or propulsion. This implies the need for an assistive device—a brace.

Paralysis of the muscles which act to flex or extend the hip, knee, and ankle not only implies the loss of a propulsion motor, but the loss of stable supporting structure as well. Until about two years ago, all methods of getting the paralyzed individual "back on his feet" were aimed at providing stable support and almost routinely sacrificed mobility in order to do this. Stability was provided either through surgical fusion of the joint, or through the mechanical equivalent in a leg brace with a locked knee or ankle. This provided good stability but poor propulsion.

A truly biomechanical approach, rather than a purely mechanical one, would provide both support and propulsion and would not require the sacrifice of one in order to obtain the other. Biomechanical principles from both normal locomotion and above-knee prosthetics were utilized to develop a design for a long leg brace including both the primary functions of the lower extremities.

The Purpose of the Long Leg Brace

In normal human locomotion, the muscles of the lower extremities perform three major functions: They accelerate, decelerate, and stabilize the limb and its various segments. When part or all of the muscles of one

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or both of the lower extremities are paralyzed by disease or trauma there is a decrease in stability, as well as in the ability to accelerate and decelerate the limb segments. In cases where the degree of paralysis is moderate, the patient may be able to walk with a gait adapted to his impediment, as when knee stability is obtained by locking the joint into extension. However, if the impairment is such that gait adaptations and the use of crutches or canes are insufficient to provide stability, the knee joint will collapse and the patient will fall and possibly injure himself if he attempts to walk. These patients must either stay in wheel chairs or wear long leg braces.

Long Leg Brace Compared to Above Knee Prosthesis

The above-knee amputee wearing a well-fitted quadrilateral suction socket prosthesis with hydraulic knee control, if given proper gait training, can walk with a very natural gait and little more consumption of energy than a normal person. The unilateral paralytic wearing a locked-knee long leg brace cannot walk nearly that well, and uses far more energy. It would seem reasonable to believe that some of the biomechanical principles of above-knee prosthetics could be used in the design of a long leg brace so that the paralytic could exhibit a more normal gait pattern with conservation of energy, and at the same time enjoy the advantages of walking with a free-swinging knee and alignment stability.

While the amputee has lost his leg above the knee, he usually retains the use of powerful hip muscles to a large degree, whereas the paralytic may have a completely flail leg from the hip down, with no active muscles at all. Others may be able to flex the hip but not extend it, or vice versa. Others can adduct the hip, but not abduct it, or vice versa. There may be various combinations and degrees of these dysfunctions ad infinitum. The above knee amputee uses his hip muscles to control his prosthesis, so designing long leg braces for paralytics who may exhibit great varieties of combinations of muscle strength is more complex in many ways than the designing of above-knee prostheses. Nevertheless, it is possible to design and build a functional long leg brace for a patient with no active hip musculature and a completely flail leg, and train him to walk with a free swinging knee and greatly improved gait. Such a patient will never walk as well as an active above knee amputee who has a well-fitted prosthesis and is trained in its use, but he will do much better than is possible with a conventional knee-lock long leg brace.

The key problem in both above-knee prosthetics and in functional long leg bracing is to provide adequate knee stability, particularly between heel strike and mid-stance, during which phase of gait a number of factors combine to make the knee joint tend to collapse. In an above knee prosthesis, knee stability is obtained through minimizing resistance to plantar flexion of the ankle at heel strike, through the hip extension force exerted by the amputee, and by the alignment, which is so arranged that the knee center is slightly posterior to the vertical line between the trochanter and the ankle center. All of these factors tend to either reduce flexion forces on, or to actually extend the knee joint, thus preventing it from collapsing.

How the Functional Long Leg Brace Works

The functional long leg brace is made up of the following components: A plastic thigh shell, similar in appearance to the upper portion of an above knee quadrilateral socket; solid bar aluminum uprights to connect the shell to the knee joints; ball bearing knee joints, with one joint lever directly in line with the bearing, the other offset one inch; solid bar aluminum uprights

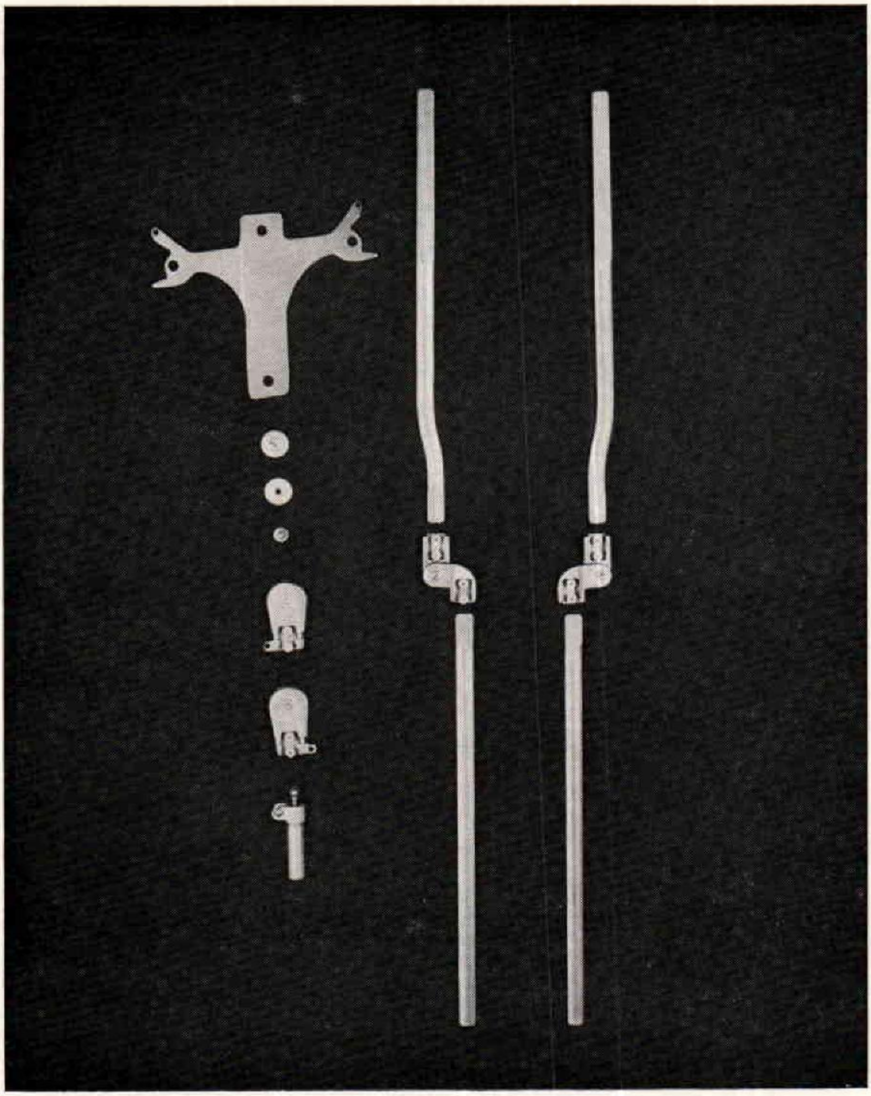

FIGURE 1

to connect the knee joints with the ankle joints; a plastic pre-tibial shell; a dacron pre-tibial cuff with Velcro fastener; heavy duty ankle joints with adjustable stops; a hydraulic damper to provide resistance to ankle dorsiflexion (optional); and a one-eighth inch thick stainless steel foot-ankle section with an anterior extension four inches long and two inches wide. (See Figures 1 and 2).

It will be easier to understand how the functional long leg brace functions if we analyze its action as the patient walks. To do this we have to have some means of identifying the activity we call walking. We will arbitrarily divide a single forward step into five phases, illustrated in Figure 3. The first phase we call "Push-off," shown in "A." Next, the knee and hip flex and the limb swings ahead, so we will call the second phase "Swing,"

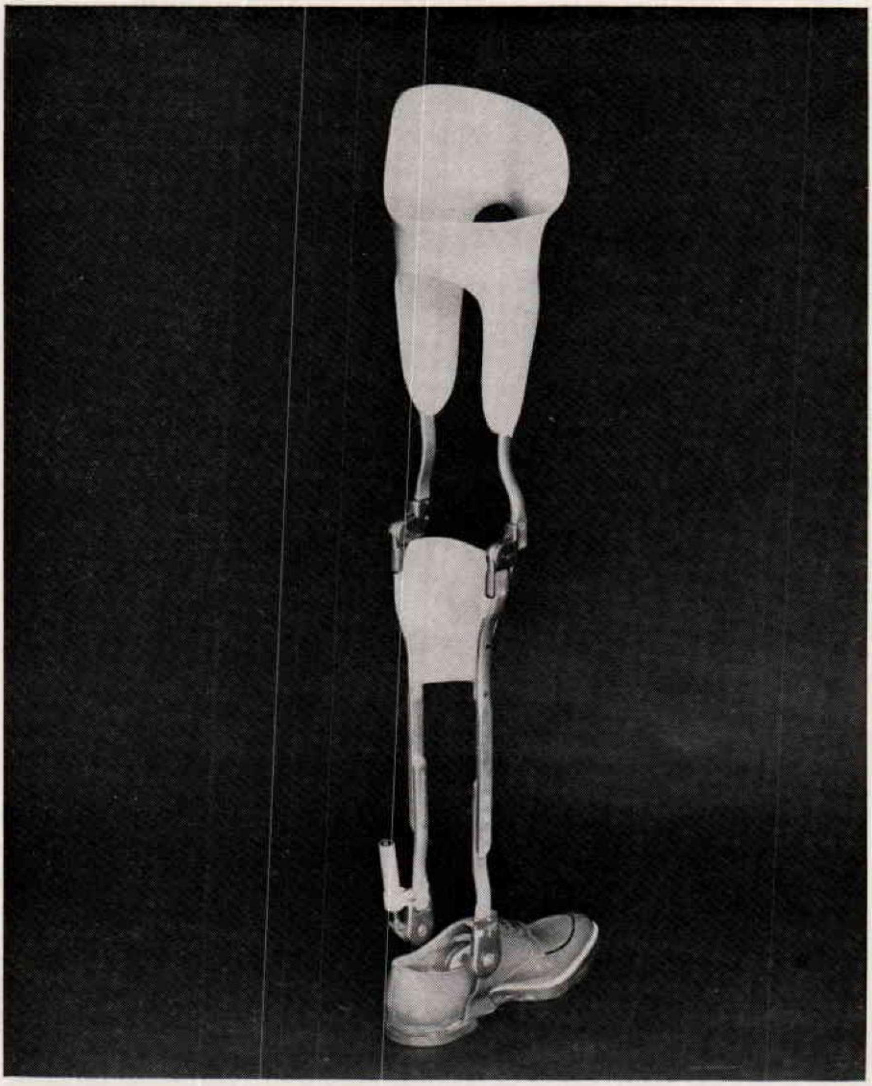

FIGURE 2

FIGURE 3

shown in "B". At the end of swing, the heel strikes the floor, so we call the third phase "Heel strike," shown in "C". An instant after heel strike the sole of the shoe comes flat onto the floor, so we will call the fourth phase "Foot flat," as in "D". The shank is still not vertical, and the movement to the vertical position from foot flat is the fifth and a very critical phase of the walking cycle. We will call the vertical position of the shank "Mid stance," shown in "E", from which the person goes on to push-off and the cycle is repeated. (This is an arbitrary breakdown of the walking cycle designed for use in describing the action of the functional long leg brace only).

To understand how the brace functions it is necessary to analyze its action in each phase of the gait cycle. At push-off the patient flexes his extended hip to bring the thigh shell forward, causing the knee joint to flex as the entire leg starts to swing forward. If the hip flexors are too weak to initiate this movement, the patient is taught to accomplish it by using his abdominal muscles to raise the hip on the affected side so gravity can cause the leg to enter the swing phase of the gait cycle. This movement, accompanied by pelvic rotation or thrust, which causes the ischial tuberosity to exert a downward force on the ischial seat of the thigh shell, will cause the hip and knee to flex and swing the leg forward. In the illustration, Figure 4, the patient has initiated his stride and is midway between push-off and swing phase. Elevation of the hip at this instant would bring the foot off of the floor and add the force of gravity to the swing of the lower leg.

During swing phase of the gait cycle, because of the inertia of the shank, the knee flexes between 45 and 60 degrees, and thus shortens the effective length of the leg enough to prevent the toe of the shoe from scraping the floor. If the hydraulic damper is used, it prevents the ankle from quickly plantar flexing, which also helps keep the toe from scraping. Of course, the presence of any active ankle dorsiflexor muscles also contributes to the lessening of this problem.

At heel strike the weight of the body on the lever arm between the ankle joint and the heel will cause a torque to develop around the ankle joint which tends to move the shank forward, causing the knee to collapse. To prevent this force from becoming sufficiently great to cause the knee to collapse, it is necessary that the foot move from heel strike to foot flat

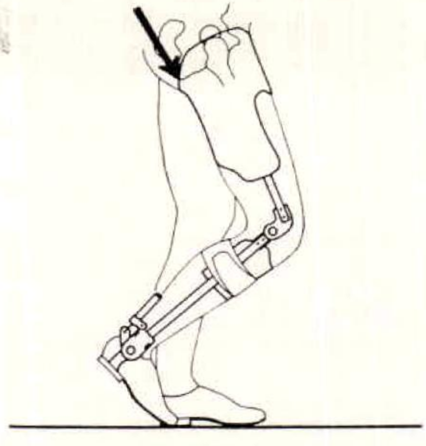

FIGURE 4

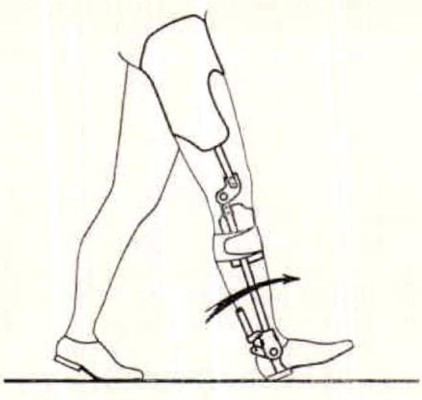

FIGURE 5

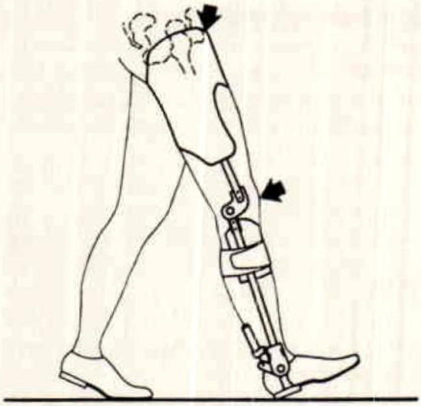

FIGURE 6

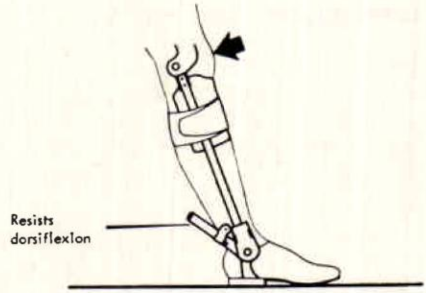

FIGURE 7

with as little resistance to plantar flexion as possible. The amount of plantar flexion with the average patient taking a normal stride is approximately 20 degrees, so the stops on the ankle joints must permit an equal amount of motion or serious knee instability will result. (See Figure 5).

In the absence of active hip extensors, the most significant knee stabilizing force between heel strike and foot flat is provided by pressure of the patient's abdomen and pelvis on the anterior brim of the thigh shell. This force is downward on the anterior brim, and since this is at a point well ahead of the attachment points of the uprights, there is a lever action which tends to force the uprights back, and so hold the knee joints in extension. The effective length of this lever arm is increased by the design of the knee joints, which have one arm offset one inch. This offset places the joint center one inch further posterior, increasing the lever effect between the anterior brim and the joint by that much. (See Figure 6).

If the patient has active hip extensors, knee instability is further minimized between heel strike and foot flat, as the power exerted by these muscles can be used to force his own knee into extension. Many patients need more knee stability during the time the shank pivots forward on the ankle joint from foot flat to mid-stance than can be provided by abdominal pressure on the anterior brim and any active hip extensors that may be present. Additional stabilizing force can be provided by the use of the hydraulic damper unit. The unit consists of a small piston and cylinder assembly so designed that oil is forced through very small orifices when the piston is moved in one direction, thus building up a high resistance. When moved in the opposite direction a check valve opens, allowing the oil to flow freely, thus reducing resistance to a very low value. The unit is mounted between the foot-ankle section and the upright in such a way that ankle flexion forces the piston back and forth in the cylinder. The unit is mounted so it will exert strong resistance to ankle dorsiflexion. As the shank pivots forward on the ankle, the effect of this resistance is to hold the knee in extension and prevent it from collapsing. (See Figure 7, showing hydraulic unit resisting dorsiflexion, causing stabilizing force on knee).

When the patient reaches mid-stance the ankle joints come up against the ankle joint dorsiflexion stops. As he rolls on over the ball of the foot the entire anterior portion of the foot becomes a lever arm through which the weight of the body exerts a torque around the ankle that tends to push the shank back, and thus holds the knee in extension. (See Figure 8, showing toe lever arm causing force tending to push knee into extension). The amount of this stabilizing force on the knee and the timing of its application can be regulated by the contouring of the sole of the shoe. This stabilizing force on the knee continues as the shank pivots forward over the ball of the foot until push-off is reached again, at which point the entire cycle is repeated.

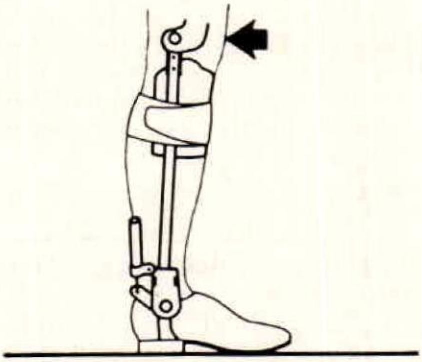

FIGURE 8

When the patient is standing still with weight on the braced leg, a substantial amount of his weight is borne by the thigh shell because of the fact that it is fitted with considerable tension. This weight is fairly evenly distributed in the shell, and is transferred to the uprights with little or no lever action. The advantage of this amount of weight bearing is the stabilizing effect it has on the pelvis. Knee stability is provided by the lever action of the one inch off-set in the knee joints.

It must be clearly understood that this is *not* an ischial weight bearing brace. Any weight on the ischial seat of the thigh shell sets up a force that tends to move the knee forward and cause it to collapse. The only time the patient may ever touch the posterior brim of the thigh shell with his ischial tuberosity is when he initiates hip flexion at push-off, and this is only the case when he has weak flexors.

The stabilizing effect of the brace is achieved through the action of the pre-tibial shell resisting the tendency of the knee to flex. The thigh shell and ankle joints provide the reaction points that make it possible for the pre-tibial shell to prevent the knee from flexing. Most of the patient's weight is borne on his own leg. It is able to do so because if his knee starts to buckle, the brace transmits the force exerted by his knee on the pre-tibial shell to the reaction points at his thigh and ankle. The brace thus serves as a splint to prevent the patient's knee from collapsing when weight is borne on it. During stance phase the brace bears some weight because of the tension of the shell on the thigh. Such weight is evenly distributed and so does not disturb the balance of forces that maintain knee stability.

In addition to its function as the means for exerting the force that stabilizes the knee, the pre-tibial shell also serves a very useful purpose by contributing to the lateral stability of the patient's knee joint. In many cases where the knee tends to bend medially or laterally when bearing weight, a well-fitted pre-tibial shell will hold the limb in line. The shell is shaped so it extends well around the calf on both sides, extends down from the lower border of the patella about one third the length of the shin, and fits the contours of the limb well enough so there is an even distribution of pressure over the entire area. A shell shaped and fitted with care will comfortably accommodate medial and lateral as well as anterior forces. Legs with considerable medial or lateral distortion can be held in the normal position in this way, and after the patient wears the brace for a time the initial discomfort of being held in a new position wears off.

The tibial cuff is attached to the pre-tibial shell, encircling the calf of the leg. It serves mainly to hold the shin firmly in the shell and so prevent abrasion, and to prevent the brace from sliding forward off the leg when the patient sits down. Since it is not required to stand any great amount of force the simple webbing and Velcro cuff is adequate.

Applications for the Functional Long Leg Brace

Every patient with lower extremity paralysis is not a candidate for a functional long leg brace. The patient who is qualified to use this brace can enjoy greater comfort, more natural gait, conservation of energy, and the convenience of no knee locks. However, the patient who is not qualified to use the functional long leg brace will not be able to enjoy these advantages, and any attempt to do so may be decidedly risky.

Some factors to consider when deciding if a patient is able to use the brace are:

1. *Weakness of trunk musculature.* If the patient's trunk muscles have been significantly weakened by paralysis, he will have difficulty walking with the brace, particularly if his leg is completely flail from the hip down.

2. *Bilateral involvement.* If both limbs are partially or completely paralyzed, the functional long leg brace is not advisable in most cases.

3. *Contractures of the knee, hip, or both.* If one or both of these joints cannot be fully extended it is very difficult to achieve alignment stability in the brace. In such cases knee locks should be used.

4. *General debilitation.* Weakness, dizziness, lack of balance, or any other physical or mental handicaps that might contribute to stumbling or falling would make the use of the brace inadvisable.

5. *Ischial weight bearing required.* Where an ischial weight-bearing brace is needed, as in case of fracture or other condition where it is desirable to transfer the weight from the ischial tuberosity directly to the floor, the functional long leg brace as described here is not suitable. The use of the plastic quadrilateral thigh and pre-tibial shells would be advantageous in an ischial weight bearing brace, but knee locks would have to be used as in the past.

6. *Paraplegia.* Paraplegics cannot benefit from the use of the brace for much the same reasons given above for bilaterals.

Because of the functional nature of the brace, the knee and ankle joints and other parts receive much more wear than is the case with the conventional brace. These parts must be made to last a reasonable length of time under conditions of hard use, and so must be made to high standards of quality and strength. Fabrication of the thigh shell and pre-tibial shell of plastic laminate requires the use of costly cast-taking equipment, and must be done to precision standards. Special parts, like the hydraulic dampers, are costly to manufacture. The dynamic alignment of the brace, which is not required with conventional braces, is time-consuming and highly technical. All these factors combine to make the cost of a functional long leg brace much greater than that of the conventional brace. However, those patients who can benefit from the functional long leg brace all agree that the additional function and conservation of energy make the additional cost worthwhile.