AN ELECTRICALLY CONTROLLED KNEE JOINT FOR LONG LEG BRACES

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Summary

Patients lacking muscular control of the knee joint can at present be fitted with long leg braces amploying either a positive knee lock to immobilize the knee or a free knee joint utilizing an offset hinge to obtain a degree of locking action during stance phase. Neither of these alternatives is entirely satisfactory since each involves compromises between optimum function and security. This paper reports some preliminary experimental results obtained with a brace furnished with an electrically controlled knee joint which is locked during weight-bearing and free during swing phase. Initial tests indicate that rapid acceptance of this type of brace can occur in a patient accustomed to wearing a conventional brace. At the present time, the electrical control concept appears to show sufficient promise to warrant development and testing.

Introduction

For those patients with flaccid paralysis of the lower limb who need a device to provide knee stability, two fundamentally different types of braces are currently available. The most common is the locked knee brace in which the knee joint remains fixed and completely stable in the extended position throughout the entire gait cycle. The other is the free knee brace which during swing phase permits unrestricted flexion and extension of the knee, while affording a degree of knee stability during stance phase.

A locked knee brace has the advantage of maintaining knee stability while walking on any surface and, in addition, can accommodate to a knee flexion contracture. Unfortunately, this leads to an unnatural gait with additional energy expenditure and the patient must adjust to advancing the limb during swing phase with a stiff and fully extended knee. In addition, the patient must unlock the knee joint before sitting and lock it again after standing up. In contrast, a free knee brace has no intrinsic locking mechanism, but provides knee stability during stance phase by having the knee axis positioned behind the center of gravity of the body. If at any time the line of body weight falls behind the eccentric knee joint, knee flexion results.

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Therefore, near vertical hip-trunk alignment is required. A patient with poor trunk control is unable to use the brace. Further, the brace cannot accommodate knee flexion contracture and can accommodate a slight hip flexion contracture only if there is adequate hip extension strength. Another problem is that the knee buckles when walking down an incline and is unstable on an uneven surface. It has several advantages, however, which include less energy expenditure, a more normal appearing gait, less difficulty in ascending and descending stairs, and no necessity of locking and unlocking the knee when rising from the sitting position or sitting from the standing position.

The research reported in this paper relates to an attempt to combine the best features of both types of knee joints described above while eliminating the undesirable features. The free knee is most desirable during swing phase, while during stance it is better to have a knee that is fixed and stable no matter where the line of the body wieght falls. Therefore, the knee joint mechanism to be described is designed to lock mechanically during stance phase and to unlock during swing phase. A positive locking action results from a spring mechanism whenever the leg is fully extended, while unlocking occurs in response to an electrical current furnished to a solenoid actuator by a control circuit.

Background and Principle of Operation

Tomović and McGhee /1/ have advanced an approach to the design of electronically controlled prosthetic and orthotic appliances which results in very simple electronic systems whenever it is applicable. This approach, called "finite state control", is based upon the observation that legged locomotion can be accomplished in many cases without requiring that the torque applied at leg joints be precisely controlled. Physiologically, this is equivalent to saying that locomotion does not always require graded muscle contraction. According to /1/, the essential features of legged locomotion in animals and man can often be realized by properly sequencing each joint into one of four distinct states. These states are: 1) free state, 2) forward rotation, 3) reaward rotation, and 4) locked state. A further aspect of the finite state approach is that the selection of the proper state for each joint need not be made on a continuous basis, but rather can be relegated to certain discrete joint positions called "decision points". This assumption allows feedback control of joint states to be accomplished with electronic circuits containing only a very small number of digital circuit components and no analog components. In /1/, it is shown how full coordination of the knee and ankle joints of a powered prosthesis for an above-the-knee unilateral amputee can be achieved with a circuit employing only 4 filp-flops.

The finite stete control approach was first successfully applied to a prosthesis in the "Belgrade Hand" /2/. This hand uses a simple digital electronic circuit to automatically regulate grasping or pinching action in an electrically powered hand prosthesis. A subsequent test of finite state concepts was provided by the successful demonstration of an artificial quadruped in which eight electrically powered joints were coordinated by an electronic sequence generator /3/. In later work, fully asynchronous locomotion of this machine was accomplished using a control computer containing only sixteen flip-flops /4/. So far as is known to the authors, the present research represents the first experimental application of finite state control concepts to human locomotion.

In the present application, it is assumed that the patient's unaided knee joint is able to provide the first three states needed for locomotion, but is unable to reliably attain a locked state during weight-bearing phases. The sole function of the appliance, therefore, is to furnish the fourth (locked) state to the knee joint at the proper points within each cycle of locomotion. This is a great simplification over the full joint control described in /1/ and a correspondingly simplified mechanism results. Specifically, all that is required of the electromechanical knee joint and its control circuits are the following actions:

1. Detect the end of the weight-bearing phase of the affected leg and unlock the knee joint.
2. Detect the end of the swing phase and lock the knee joint prior to heel strike.

In the system which has been tested, the first function is accomplished by a solenoid actuated by a mercury switch to unlock the knee. The mercury switch is attached to the upper part of the brace and is adjusted to an angle such that the solenoid is energized when the hip joint reaches its normal reaward limit of rotation corresponding to the end of weight-bearing. The locking function is accomplished mechanically only when the leg has been fully straightened prior to heel strike. Details of the electrical and mechanical design of the brace and knee joint mechanism are provided in the following discussion.

Mechanism

Thus far, two distinct types of knee joint mechansms have been designed and tested in this research program. The first brace used was a conventional long leg brace furnished with a gravity drop ring lock modified to allow electrical unlocking. Figure 1 illustrates the operation of the modified lock. As can be seen, a latching action is provided by a spring mechanism which holds the ring in the unlocked position once it has been pulled up by the solenoid. This feature allows reliable unlocking to occur as a result of a short current pulse being delivered to the solenoid, thereby eliminating the need for continuous solenoid action and greately reducing the average power requirements of the electrical circuit. Figure 2 shows the electrical circuit used to power the unlocking solenoid. In this figure, S_1 is a switch used for selecting either a manual or automatic mode of operation, S_2 is a switch for locking or unlocking the knee joint in the manual mode, and S_3 is the mercury switch which operates the solenoid in the automatic mode. Figure 3 is a close-up view of the experimental system, showing the attachment of the electrical components to the brace. In this particular model, the mercury switch, S_3, was located at the ankle joint and thus does not appear in the photograph.

Experimentation with the ring lock brace showed that while the action of the electrical circuit was quite satisfactiry, the force produced by the solenoid was inadequate to reliably overcome the frictional force associated with the ring lock. Accordingly, three corrective modifications were made. First of all, the ring lock was abandoned in favor of a Swiss or "bail" lock /5/ in order to reduce the force required for unlocking. Secondly, a much larger solenoid was installed on the new brace. Finally, to further increase the unlocking force available from the solenoid, the battery and capacitor power source shown on Figure 2 were replaced by a 110 volt AC power source connected to the brace by a trailing line cord. Figure 4 shows the modified system fitted to a patient.

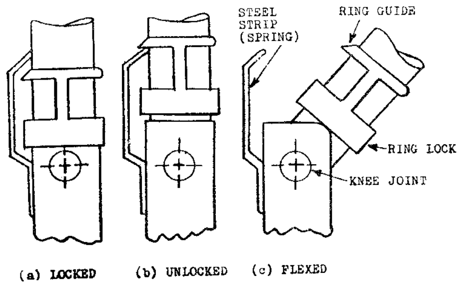


Fig. 1. Ring lock modified for electrical unlocking.

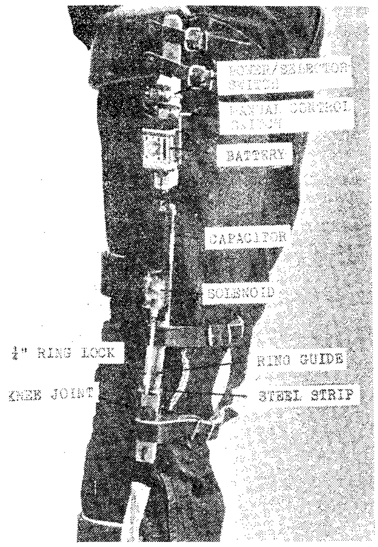


Fig. 3. Ring lock leg brace showing electrical components.

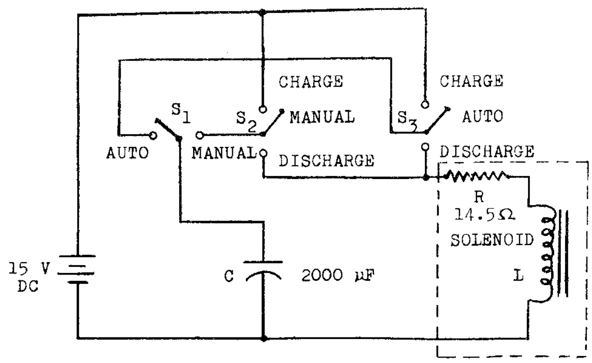
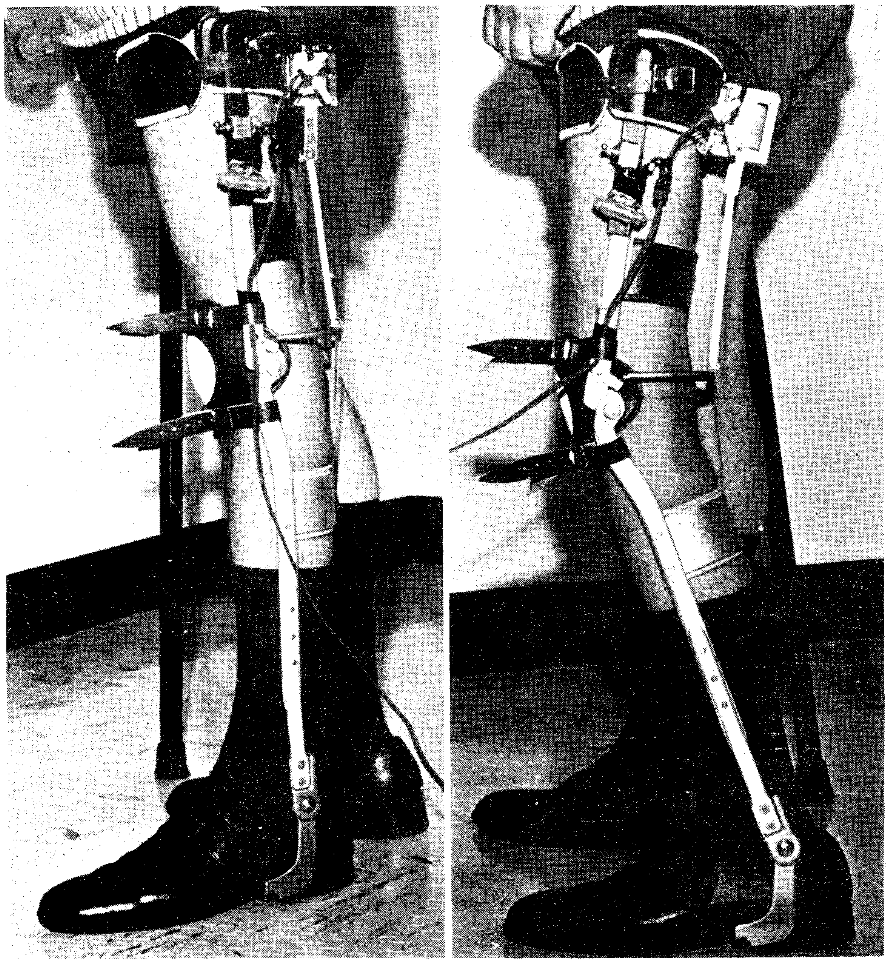


Fig. 2. Solenoid control circuit

Experimental Results

The battery powered ring lock brace proved to be functionally effective when worn by a normal subject provided that the user was careful to over-extend his knee prior to toe-off at the end of each stride. It was found that this action relieved the frictional loading on the ring lock sufficiently to permit reliable unlocking. However, it was felt that such an action demanded too much conscious attention by the subject and might not even be possible in cases of knee instability, so the ring lock approach was abandoned.



(a) (b)

Fig. 4. Swiss lock brace with electrically controlled knee joint
(a) locked
(b) Unlocked

The electrical system attached to the Swiss lock brace shown in Figure 4 was deliberately over-designed to ensure dependable operation in tests with a disabled subject. As a consequence, no difficulaties were experienced with the locking and unlocking action. Indeed, the test subject, who was accustomed to wearing a free knee joint brace, adapted to the automatic knee joint action within a matter of minutes and found it a pleasant experience to wear the brace. His only objections related to the obvious annoyance of the trailing power cord and to the rather loud clicking noises made by the solenoid and locking mechanism during locomotion. Otherwise, no difficulties were experienced with acceptance of the brace by the patient during initial testing.

Conclusions

Much more research will be needed before it can be stated with confidence that the approach reported here can produce a clinically acceptable orthotic appliance. It will certainly be necessary to at least combine the best features of the two braces described above to produce a self-contained battery powered brace with a very reliable locking and unlocking action. In addition, it would be highly desirable to reduce the noise associated with locking and unlocking and also to provide the knee joint with one or more additional locking positions with the knee partially flexed. The latter modification could reduce the likehood of knee joint collapse in the event that full extension failed to occur prior to heel strike. It is also likely that a better type of bearing will be needed in the knee joint to permit operation through a great many cycles without excessive wear. No doubt further testing will reveal other desirable changes in both the electrical and mechanical parts of the brace.

Despite the evident shortcomings of the present experimental braces, this research project has demonstrated the applicability of finite state control to orthotic appliances for the lower extremities. While testing to date has been limited to just one session with a single patient, this individual accepted the brace immediately and definitely preferred it to the alternatives of a conventional locked or free knee joint long leg brace. It is felt that this result is sufficiently encouraging to justify further development and more careful evaluation of long leg braces employing electronic and electro-mechanical components for automatically coordinated locking and unlocking of the knee joint.

Acknowledgements

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