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Friedman

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[54] **END POINT CONTROL OF UPPER EXTREMITY ORTHOTIC BRACE USING HEAD ORIENTATION**

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[52] **U.S. Cl.** .... **3/1.1**, 128/25 R, 214/1 CM
[51] **Int. Cl.** **A61f 1/00**
[58] **Field of Search** .... 3/1–1.2, 3/12, 12.8; 128/25 R, 26, 77; 214/1 CM

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Assistant Examiner—Ronald L. Frinks
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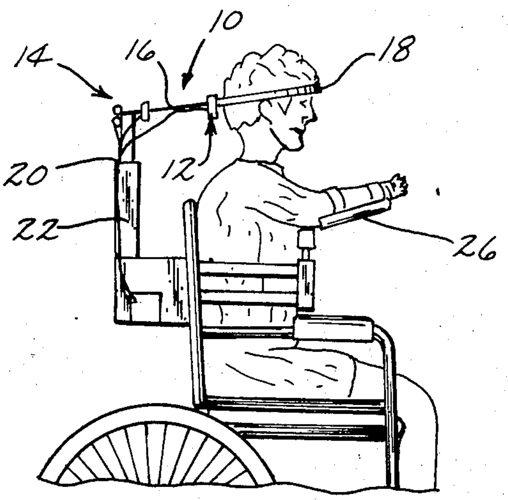
[57] **ABSTRACT**

An end-point control of an upper-extremity orthotic brace employing head orientation is disclosed herein which is particularly well suited for quadriplegics who are able to spend some portion of their day in a wheel chair. A first gimbal is detachably secured to the patient's head by means of a head strap or the like and is interconnected by a shaft to a second gimbal which is secured to the wheel chair. The first and second gimbals have responsive means thereon such as single turn potentiometers which are responsive to azimuth, elevational and range movements of the patient's head. A control system is connected to the potentiometers for driving a powered device such as an arm brace so that the patient can control the operation of the arm brace through coordinated head movements.

10 Claims, 11 Drawing Figures



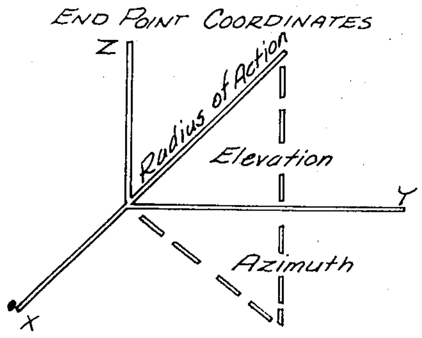


Fig. 1

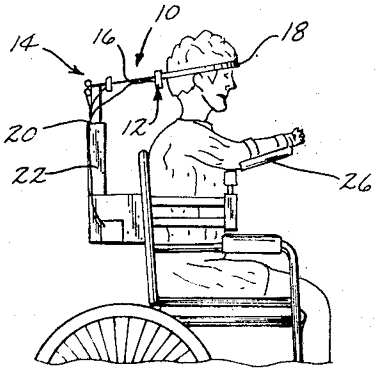


Fig. 2

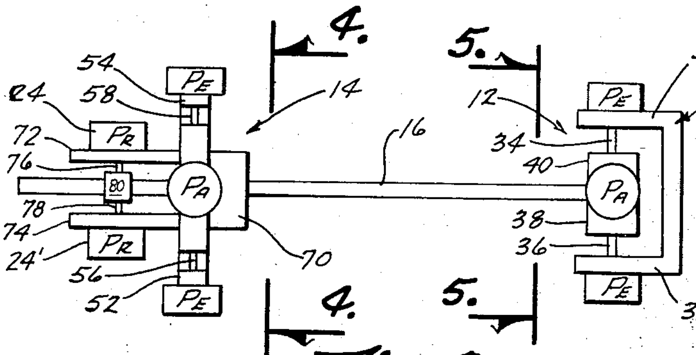


Fig. 3

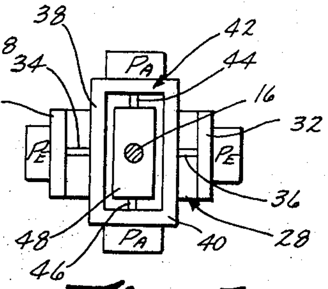


Fig. 5

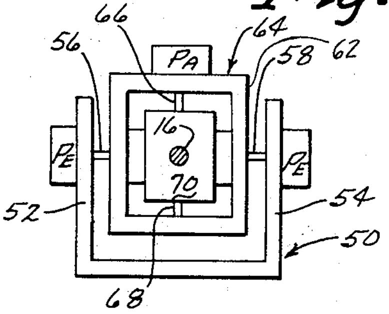


Fig. 4

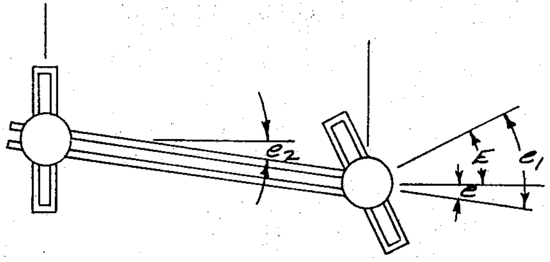


Fig. 6

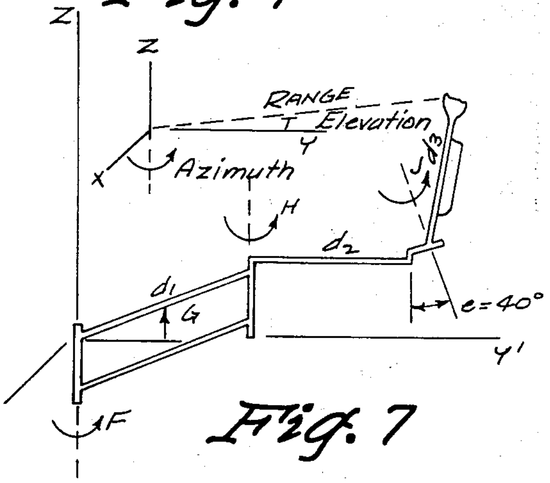


Fig. 7

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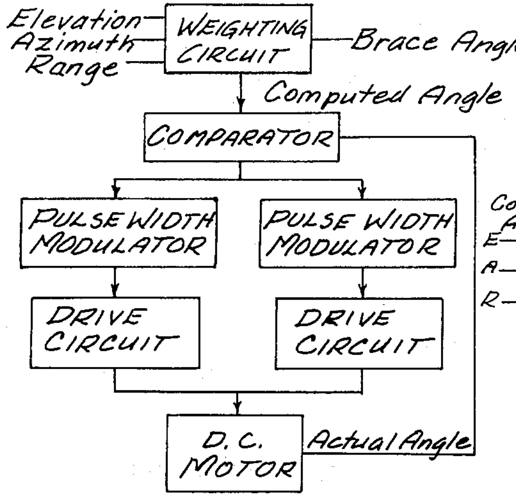

Fig. 8

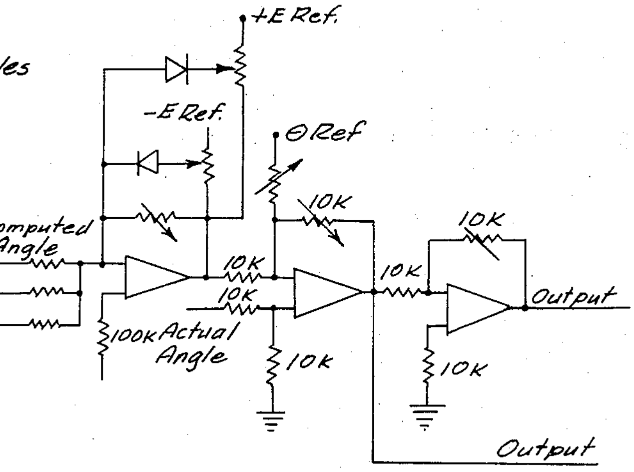

Fig. 9

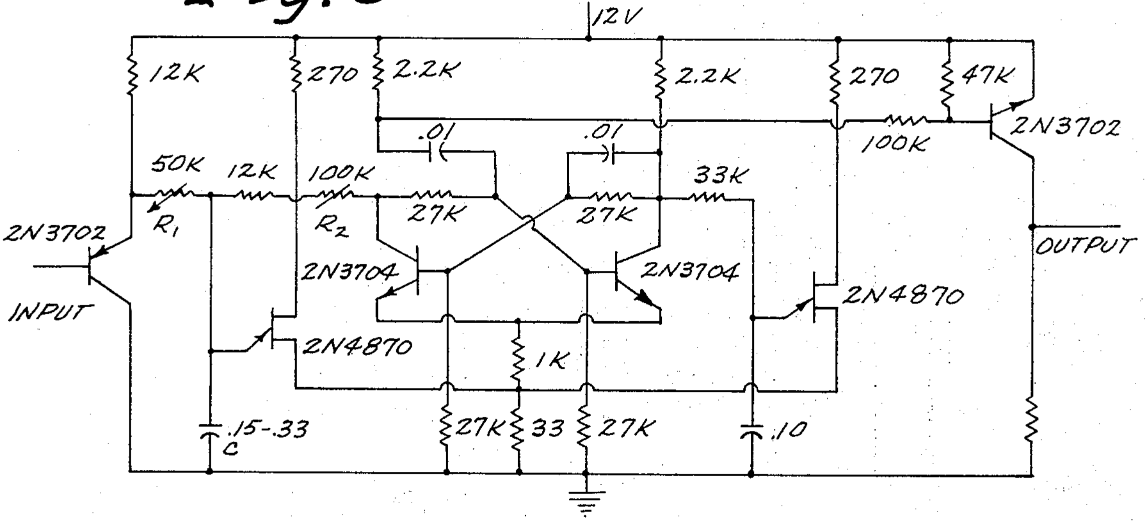

Fig. 10

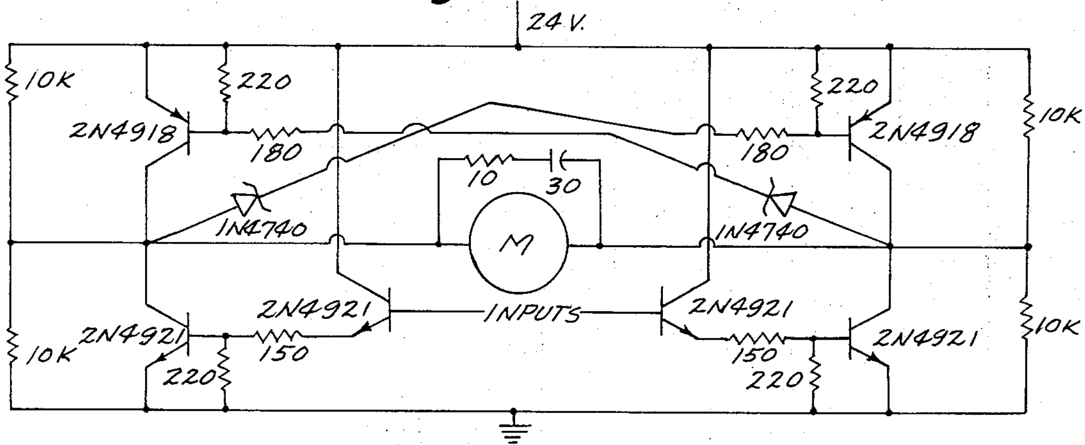

Fig. 11

END POINT CONTROL OF UPPER EXTREMITY ORTHOTIC BRACE USING HEAD ORIENTATION

In recent years an increasing number of people are surviving accidents or neuromuscular diseases with extensive paralysis. Typically such disability occurs in persons who have suffered poliomyelitis, muscular dystrophy, cerebral palsy, or lesions in the fourth or fifth cervical spinal cord region. Even though modern medicine is conquering polio through vaccination, there are an increasing number of paralysis victims resulting from automobile accidents and hostilities such as Vietnam.

Quadriplegics, those experiencing paralysis of all four limbs, are normally bedridden, but may spend some portion of their day wheel chair bound. Generally, such patients while lacking function in their upper-extremities do retain normal muscular control from their shoulders upward including, in some cases, the ability to raise and lower the shoulder girdle.

The problem of restoring limited function by means of external mechanical devices, termed upper-extremity orthotics, is complex for any such mechanism must be built to follow the anatomical joints and support the flail extremity along with performing nearly normal upper-extremity motion. The control of such an orthotic device is particularly difficult for severely handicapped patients requiring multi-degree of freedom assistive braces and possessing few functional residuals for control signal sources.

The rehabilitation of upper-extremity function through orthotic devices is doubly challenging for any solution must be both technologically sound and psychologically acceptable to the patient. Realistically, one must accept the fact that a mechanical device will never satisfactorily substitute for a normally functioning limb. However, the objective of the rehabilitation of a patient is not to enable him to perform tasks more efficiently than could be done by an attendant, but is to provide some degree of functional independence and associated personal satisfaction. It is of psychological advantage to allow the patient continuous voluntary control over the system rather than merely initiating a fully automated sequence even though its performance might be superior. From a purely mechanical standpoint, it would be much easier to design a manipulator which would execute a programmed routine, but it is generally agreed that mobilizing an existing arm and actively involving the quadriplegic in the control system are beneficial in minimizing the feeling of being a "mechanical man" and encouraging any possible increase in residual limb function.

During the past decade researchers have developed numerous upper-extremity orthotics to provide partial return of arm function to severely paralyzed patients. Although designers have shown awareness of control and feedback, their primary attentions have been directed toward the powering and fitting of assistive devices. Present state of the art is such that the necessary hardware can be built; but there are serious problems involved in designing effective control systems. At the present time such control systems are in a rudimentary stage.

Investigations have been conducted in many areas including studies regarding brace configuration, actuator types, modes of control, and suitability of various control sites. It appears that the only complete agreement among researchers concerning these topics is that there is general disagreement regarding the correct approach to the problem.

Arm function is extremely complex; in fact, there are eleven degrees of freedom in the arm not including the hand. The trend in the development of orthotic brace configurations has been to increase the number of degrees of freedom in the hope of providing a more flexible and functional brace. One of the latest devices, the Rancho Electric Arm, has 7° of freedom which is thought by some investigators to be the minimum number required to restore reasonable arm movement. These seven joints include two joints at the shoulder, two at the elbow (one flexion/extension and the other humeral rotation), forearm rotation, wrist flexion and hand prehension. However, generally associated with an increase in the number of degrees of freedom is an undesirable increase in the bulk of the brace and complication of the control system.

The decision regarding whether to use pneumatic or electrical actuators to operate an orthotic brace is not clear-cut even though several studies have been conducted in this area. However, both types of actuators have been used successfully and their performance is comparable. The most widely used external-power source has been CO_2 gas in the pneumatic systems. The actuators for these systems are pistons and McKibben artificial muscles. More recently electrical systems have been used with permanent magnet 24 volt D.C. motors as actuators.

Studies in the past have concentrated on two basic approaches: first, to operate an orthotic brace completely by direct patient control, and second, to make such control fully automatic. In direct control schemes, the patient excercises continuous control over the motion of the assistive device. Automatic control, once initiated allows a movement to progress to its completion without further conscious attention. There are obvious problems with both methods.

Direct patient control is difficult because of the number of degrees of freedom which must be controlled. Devices in this category presently require separate sites or switches to control each joint of the brace. The disadvantages of this type of system are that coordinated motion of the brace is difficult since multiple sites must be activated simultaneously and smooth positioning of the brace is relatively unobtainable with an on-off control system. The results of one study indicate that a polio patient required 150 motions to take five bites of food and 45 motions to pick up a cup and drink from it using the direct type of control. In general, presently developed systems require a degree of mental attention that is excessive, particularly in terms of the frequently unnatural motion that results.

On the other side of the spectrum is the completely automatic device in which the patient simply selects which one of several programmed motions will be performed. There are several problems associated with this approach including reduced adaptability due to a limited number of movement sequences, the expense of peripheral equipment normally associated with such a system, and substantially reduced patient participation.

In recent years, one of the most active areas of interest has been in discovering anatomical sites which are suitable for generating control signals. Many exotic control sources have been proposed for severely paralyzed patients having limited effector sites. In general, higher order quadriplegics have only the following control sites available: relative motions of body parts above the shoulders, electromyographic signals (EMG), electroneurographic signals (ENG), electroencephalographic signals (EEG), and sound or speech.

Investigators have considered several schemes for transforming relative motion of parts of the body into usable signals. Included among these studies have been attempts to use head motion to actuate simple arrays of switches, a light source attached to eyeglasses that may be directed to activate appropriate photocells, and switches activated by eyebrow motion. One of the most commonly used techniques has been the operation of a switch or strain gauge array by means of the tongue. One of the latest approaches has been an attempt to use eyeball motion as the signal source. This method utilizes the fact that light shining on the eye is reflected back toward the source in varying amounts depending on the eye orientation. Eye motion will eventually be used to generate signals for azimuth and elevation inputs to a coordinate converter. Preliminary findings indicate that drift, blinks, and light intensities will be a major source of problems.

Electromyographic signals, the electrical activity associated with muscle activity, have been used in various control schemes. The main problem with such systems has been the excessive amount of effort required to activate multiple sites in comparison to the minimal function provided. Electroneurographic signals, the potential activity from the nerves, and electroencephalographic signals, the potential activity of the central nervous sytem, have been proposed as signal sources, but present techniques and signal pattern recognition problems make them impractical. The use of sound or speech to activate electrical circuits by using acoustical filters appears feasible, but again the control of several actuators by this method would be difficult and its operation would limit communication of the patient during brace operation.

The state of the art is such that systems presently developed or being developed provide limited restoration of upper-extremity function, but either require extreme effort to generate coordinated motion or totally lack active patient participation.

Therefore, it is a principal object of this invention to provide an end-point control of an upper-extremity orthotic brace using head orientation.

A further object of this invention is to provide a means for controlling a powered device using head orientation.

A further object of this invention is to provide a gimbal which is secured to the patient's head by a head strap and which is interconnected by a shaft to a second gimbal which is secured to the wheel chair, the gimbals and shaft permitting the reading of azimuth, elevational and range changes in the head position.

A further object of this invention is to provide a device having two sets of gimbals to measure the actual angles of azimuth and elevation as referenced to the wheel chair.

A further object of this invention is to provide a control system for operating an orthotic brace through vertical, horizontal and rearward and forward head movement.

These and other objects will be apparent to those skilled in the art.

This invention consists in the construction, arrangements and combination of the various parts of the device, whereby the objects contemplated are attained as hereinafter more fully set forth, specifically pointed out in the claims, and illustrated in the accompanying drawings, in which:

FIG. **1** illustrates the end-point coordinates;

FIG. **2** is a side view illustrating the end-point control of an upper-extremity orthotic brace;

FIG. **3** is a top view of the gimbal arrangement;

FIG. **4** is a front view of the fixed gimbal;

FIG. **5** is a front view of the head mounted gimbal;

FIG. **6** schematically illustrates the manner in which the elevation angle is measured;

FIG. **7** schematically illustrates the brace axes;

FIG. **8** is a schematic illustration of the control system;

FIG. **9** is a schematic illustration of the electrical circuitry of the weighting circuit and comparator;

FIG. **10** is a schematic illustration of the electrical circuitry of the pulse width modulating circuit; and

FIG. **11** is a schematic view of the electrical circuitry of the motor drive circuit.

Based on the limitations of existing upper-extremity orthotic systems, the design of an improved assistive device requires the selection of a more suitable control site. The desire to initiate movement of an orthotic device originates at some conscious level in the central nervous system and takes the form of some voluntary physical action. Head orientation is particularly suited as a control site, since the head has its own vertical sensing element and smooth control of head motion over a wide dynamic range is possible.

Azimuth, elevation, and radius of action together generate a vector-distance function that can serve to specify the end-point coordinates or an orthotic brace. This end-point coordinate system, shown in FIG. **1**, is in the form of spherical coordinates. Positions of the hand that are normally traversed in routine self-care activities may be specified in terms of this vector-distance function.

An array of transducers was designed and constructed to provide a continuous measurement of the angular orientation of the head together with a simulated signal of "desired range" based on head position. This device is shown in FIG. **2** and is generally identified by the reference numeral **10**. Device **10** generally consists of two gimbals **12** and **14** interconnected by a small aluminum shaft **16** which senses movements of gimbal **12**.

Gimbal **12** is strapped to the patient by an elasticized headband **18** and the second gimbal **14** is attachd to a mounting **20** on the back of the wheel chair **22**. The device allows the patient to rotate his head approximately 100° in the vertical plane and **80** degrees in the horizontal plane with negligible restraint. The only significant restriction is in the forward-backward motion of the head which is limited to approximately two inches of travel by the range transducer.

It is necessary to use two sets of gimbals to measure the actual angles of azimuth and elevation as referenced to the wheel chair. As shown in FIG. **6**, the true elevation angle is obtained by adding the corresponding angles of both gimbals. This same relationship holds true for measuring azimuth. Thus, the gimbal **14** mounted on the wheel chair measures the necessary correction to account for the fact that the gimbal **12** strapped to the patient measures angles with respect to the interconnecting shaft **16** rather than to a fixed set of axes.

A radius of action or "desired range" is simulated by the patient's relative forward-backward positioning of his head which is converted from a linear displacement of the interconnecting shaft **16** to the rotation of potentiometers **24** and **24'**. Minimum range is selected by the patient moving his head to the most forward position, a somewhat natural eating posture. Range is increased by the patient moving his head backward.

More specifically, gimbal **12** comprises a U-shaped yoke **28** which is strapped to the patient's head. The legs **30** and **32** of yoke **28** have potentiometers P_E mounted thereon respectively which are operatively connected to the shafts **34** and **36** extending inwardly from legs **30** and **32** respectively. The inner ends of shafts **34** and **36** are rigidly secured to sides **38** and **40** of block **42**. Potentiometers P_A are mounted on the top and bottom portions of block **42** and are operatively connected to the shafts **44** and **46** extending from block **42**. The inner ends of shafts **44** and **46** are rigidly secured to support **48** which is secured to shaft **16**. Thus, movement of the patient's head is an upwardly direction causes yoke **28** to rotate or pivot with respect to shafts **34, 36** and the block **42**. Such movement of yoke **28** causes the shafts **34** and **36** to change the resistance of the potentiometers P_E due to their connection with the shafts **34** and **36.**

Movement of the patient's head in a sideway manner causes yoke **28** to in turn rotate or pivot block **42** with respect to support **48** and shafts **44, 46.** Such movement causes shafts **44** and **46** to change the resistance in the potentiometers P_A due to the connection therewith. Forward or backward movement of the patient's head causes shaft **16** to be correspondingly moved. The patient can simultaneously control potentiometers P_A and P_E by moving his head sideways and vertically.

Gimbal **14** comprises a U-shaped yoke **50** which is secured to the wheel chair. The legs **52** and **54** of yoke **50** have potentiometers P_E mounted thereon respectively which are operatively connected to the shafts **56** and **58** extending inwardly from legs **52** and **54** respectively. The inner ends of shafts **56** and **58** are rigidly secured to sides **60** and **62** of block **64**. Potentiometer P_A is mounted on the top of block **64** and is operatively connected to the shaft **66** extending from block **64**. A shaft **68** also extends from block **64**. The inner ends of shafts **66** and **68** are rigidly secured to support **70**. Shaft **16** slidably extends through support **70.** Rotational movement of shaft **16** causes pivotal movement of support **70** by means of a keyway arrangement. Support **70** has a pair of rearwardly extending legs **72** and **74** having the range potentiometers P_R mounted thereon. The shafts **76** and **78** are connected to the potentiometers P_R and have a gear or roller **80** mounted thereon which engages the shaft **16** to sense any longitudinal movement of the shaft **16.**

Thus, elevational movement of the patient's head causes shaft **16** to pivot support **70** and block **64** with respect to yoke **50** so that the resistance in the elevation potentiometers P_E is changed. Sideways movement of the patient's head causes shaft **16** to pivot support **70** with respect to block **64** to change the resistance in the azimuth potentiometers P_A. Longitudinal movement of shaft **16** (range) causes the resistance to be changed in the range potentiometers P_R.

Head orientation is well suited as a control site because of the ease in measuring a set of coordinates which fully specify the desired end-point of an orthotic brace **26.** This natural signal source requires minimal concentration, effort, and training to activate. It allows a patient to directly control the trajectory of an assistive device through head motion, is cosmetically acceptable, and places few restrictions on patient movement.

The orthotic brace **26** is shown in FIG. **2** and is readily available. The brace **26** was originally designed as a pneumatically actuated feeder but has been converted to electric motor drive. Electrical actuators are preferred since there is a ready source of battery power in the electric wheel chairs.

The orthotic brace **26** allows for three powered motions; a horizontal displacement, a vertical displacement, and an elbow flexion/extension. The horizontal and vertical displacements are completely independent motions and together contribute to the abduction/adduction and flexion/extension of the upper arm. A coiled spring lessens the effects of gravity by assisting in the vertical support of the brace and the arm. A telescopic rod and tube connected to the elbow flexion/extension unit serves as an attachment for the hand support. A molded elbow and forearm trough is attached to this unit and acts as a support for the forearm which is held secure in the trough by a Velcro strap. There are several sites for adjustment of the orthosis to assist in the fitting of patienls.

The exact power requirements of upper-extremity orthotics are difficult to define, not only because of the wide age span of patients, but also because of variations in size from an atropied limb to a normal limb. To allow for this wide range of torque requirements permanent magnet motors with linear load-speed curves are utilized with adjustable gain drive circuitry. These 24 volt D.C. motors have planetary ger heads with a 639:1 gear reduction and provide the capability of 288 oz. in. torque under continuous load conditions. This type of motor is particularly desirable because of its relative compactness and light weight. Although there is some noise associated with their opeation, it is not distracting and may provide some useful function as an audible feedback.

All joints of the orthotic brace, three driven and one free, are continuously monitored by transducers. These small potentiometers provide measurements of the brace angles and are mounted with couplings which allow easy adjustment for proper reference.

The control system was designed to be "volitional", "proportional", and "vectorial". "Volitional" means the patient can start, stop, or modify the course of action. "Proportional" control means that by varying his motion the patient can control the rate of action or the force exerted. Finally, "vectorial" control means that a particular motion can be achieved in a smooth direct fashion rather than in a sequence of motions about different axes.

The overall scheme behind this design involves the theory of end-point control in which the parameter to be specified is position and the control signal is in terms of a desired end-point. Most simply stated, this system allows a patient to regulate the location of his hand through head orientation. To fulfill the requirements of end-point control it is necessary to generate control equations which fully express the relationship between the head oriented coordinates and those of the orthotic brace.

FIG. 7 is a diagrammatic representation of both the brace and head oriented coordinate systems. The brace angles include: F, the motor driven brace angle in horizontal displacement; G, a motor driven brace angle in the vertical plane; and J, a motor driven angle of elbow flexion/extension. The axis of rotation for angle J is offset 40° from the vertical thereby giving this motion both a vertical and horizontal component.

The equations expressing the relationship between the head oriented coordinate system and the orthotic brace coordinate system, in terms of a desired end-point (x, y, z), are as follows:

$$x\colon R\cos E\sin A = d_1\cos G\sin F + d_2\sin(F+H) + (d_3\cos\theta + (d_3 - d_3\cos\theta)\sin J)\sin(F+H+J) + K_x$$

$$y\colon R\cos E\cos A = d_1\cos G\cos F + d_2\cos(F+H) + (d_3\cos\theta + (d_3 - d_3\cos\theta)\sin J)\cos(F+H+J) + K_y$$

$$z\colon R\sin E = d_1\sin G + d_3\sin\theta\cos J + K_z$$

where,

$d_1 = 7\frac{1}{2}$ inches
$d_2 = 7\frac{1}{2}$ inches
$d_3 = 18$ inches
$\theta = 40°$

The K_x, K_y, and K_z terms account for the respective x, y, and z displacements between the two sets of axes and are dependent upon the adjustment of the brace in fitting a patient.

However, these exact equations are relatively complex trigonometric expressions and their solution requires considerable computational equipment or a costly series of resolver chains in place of the low cost potentiometers. At the sacrifice of some accuracy, but with considerable cost reduction, a simplified set of control equations are used. These equations are based on the geometry of the brace along with some consideration for the natural motion that is being simulated. The result of this simplification is an algorithm of weighting factors which can be optimized to satisfactorily duplicate natural arm motions and to minimize the error in the end-point positioning of the brace with respect to head orientation.

The horizontal and vertical displacements of this assistive device are completely independent motions, but actuation of the elbow flexion/extension unit results in both horizontal and vertical components. A straightforward way of relating the head generated signals of azimuth, elevation, and range to the motorized angles of the brace is to assume that the elbow flexion/extension actuator is primarily involved in changing the "desired range" of the hand. This assumption is reasonably valid in that the actuators controlling horizontal and vertical displacements by themselves have minor effects in changing the radius of action of the hand. Based upon these approximations, the actuator for horizontal displacement, angle F, and the actuator for vertical displacement, angle G, are coupled to "desired range" signals to compensate for the fact that elbow flexion/extension has components besides range associated with its motions. These greatly simplified control equations are as follows:

$$A = K_1\,(F+H)$$
$$E = K_2G$$
$$R = K_3(F+H) + K_4G - K_5J$$

where all K terms are experimentally determined weighting factors. There are two major sources of error which limit the accuracy of this approach. First, the horizontal and vertical components associated with elbow flexion/extension are not linear functions of angle J as assumed in the equations above. And second, motions produced by the horizontal and vertical actuators do have components of range involved with their displacements which are not reflected in the control equations. However, despite these limitations the expressions appear to be useable.

FIG. **8** is a block diagram of the overall control system for one motorized component. Azimuth, elevation, range, and appropriate brace angles are weighted together by a resistive network and the result, a computed angle, is compared to the actual brace angle. This is accomplished by the differential amplifier arrangement shown in FIG. **9.** The two outputs of this circuitry are directly related to the magnitude of the error existing between the desired and the actual brace angle, but are inversely related to each other about a 6 volt D.C. reference. The next stage of the electronics consists of a pair of pulse width modulating circuits, shown in FIG. **10.** If an output from the comparator stage exceeds a prescribed level, which is adjustable, the pulse width modulating circuit will generate a signal with a duty cycle which is a function of the error. Both the "dead zone" and the gain of this circuit are adjustable thereby allowing the control sensitivity, motor speed, and "dead zone" to be matched to the limitations and requirements for a particular direction and speed of an actuator to drive the error within an allowable range. Each of these circuits is mounted on an individual printed circuit board and inserted in a rack mounted on the back of the wheel chair. Two 12 volt D.C. batteries, connected in series, are used as a power source for both the motors and the electronics.

This control system acts as a simple servomechanism by which a signal, computed angle, is compared with the actual position of a joint and this error signal serves to operate actuators to null or minimize that error. This design depends to some extent on visual feedback for correcting errors in the positioning of the brace which are a result of simplifying the control equations and in the fine positioning required for performing precision tasks. Audio feedback from the electric motors may be useful in sensing the external load and/or the velocity of the limb.

The system disclosed herein provides the severely paralyzed patient with a simple, low cost assistive device which can be operated with minimal effort, concentration, and training. The key feature in this design is the use of head orientation as the controlling signal. This natural site of independent motion in azimuth and elevation is cosmetrically acceptable, allows the patient to excercise direct control of the orthotic brace, and greatly simplifies the control problem by expressing all parameters in terms of the desired end-point.

While the gimbal arrangement has been described herein as being well suited for controlling devices such as an orthotic brace, it should be noted that the gimbal arrangement could be used to control devices other than orthotic braces. Head orientation could be used by any patients with upper extremity handicaps to operate manipulators, typewriters, etc.

Thus it can be seen that a novel system has been provided which permits the severely paralyzed patient to operate a device through the use of head orientation. Thus it can be seen that the device accomplishes at least all of its stated objectives.

I claim:

1. In combination,

a chair means for supporting a patient therein;

a first gimbal means for detachable connection to the patient's head,

a second gimbal means secured to said chair means,

interconnection means interconnecting said first and second gimbal means for sensing movement of said first gimbal means in response to head movement,

said first and second gimbal means having responsive means thereon which is responsive to azimuth, elevational and range movements of the patient's head,

a powered device,

and a control system connecting said responsive means and said powered device to permit the patient to control the operation of the device by head movements.

2. The combination of claim **1** wherein said powered device is an orthotic brace.

3. The combination of claim **2** wherein said brace is an upper extremity brace.

4. The combination of claim **1** wherein said chair means is a powered wheel chair, said control system being mounted on said wheel chair.

5. The combination of claim **1** wherein said interconnection means comprises a shaft.

6. The combination of claim **1** wherein said responsive means comprises potentiometers which are operatively secured to said first and second gimbal means.

7. The combination of claim **5** wherein said first gimbal means comprises first and second supports which are pivotally movable with respect to each other, said responsive means on said first gimbal means comprising first and second potentiometer means connected to said first and second supports and being responsive to relative movement of said supports.

8. The combination of claim **7** wherein said second gimbal means comprises a third support secured to said chair means, a fourth support pivotally secured about a horizontal axes to said third support and a fifth support pivotally secured about a vertical axes to said fourth support, said fifth support being secured to said shaft and being movable therewith during the elevational and azimuth movements of the patient's head, said responsive means comprising third and fourth potentiometer means operatively secured to said third and fourth supports, said third potentiometer means being responsive to relative movements of said fourth support with respect to said third support, said fourth potentiometer means being responsive to relative movement of said fifth support with respect to said fourth support.

9. The combination of claim **8** wherein a fifth potentiometer means is operatively secured to said shaft which is responsive to longitudinal movements thereof.

10. In combination,

a chair means for supporting a patient therein;

a first support means for detachable connection to the patient's head,

a second support means secured to said chair means,

interconnection means interconnecting said first and second support means for sensing movement of said first support means in response to head movement,

said first and second support means having responsive means thereon which is responsive to azimuth, elevational and range movements of the patient's head,

a powered device,

and a control system connecting said responsive means and said powered device to permit the patient to control the operation of the device by head movements.

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