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A Technical Note

Instrumented parallel bars for three-dimensional force measurement

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Abstract—This paper describes the modification and instrumentation of standard parallel bars to allow for the measurement of applied forces on both horizontal bars in three dimensions. This measurement system has been used in the development and evaluation of functional electrical stimulation (FES) devices for standing and gait restoration in paralyzed patients. Real-time measurement of forces applied by the upper body of the patient to the parallel bars is of use in the evaluation of FES stimulation patterns (or automatic controllers of stimulation). Such measurements are useful in the redesign of stimulation patterns and/or stimulation controllers.

Key words: *force measurement, functional electrical stimulation, parallel bars, paraplegia, rehabilitation.*

INTRODUCTION

This paper describes the development of a parallel bar system to obtain measurements of the forces exerted by the hands of a subject during electrically stimulated standing (1,2), gait (3), and stair climbing and descent. The knowledge of the magnitude and directions of hand support forces is important information in the development of improved functional electrical stimulation (FES) systems. Real-time measurement of forces applied by the upper body of the patient to the parallel bars are of use in the evaluation of FES stimulation patterns (or automatic controllers of stimulation). Such measurements are also helpful in the redesign of stimulation patterns or stimulation controllers. For example, in the development of improved FES standing systems that allow patients with paraplegia to perform one-handed tasks, real-time measurements of the corrective forces applied by the other hand (to maintain patient posture) provide a measure of the effectiveness of lower extremity FES controllers in maintaining posture. In the development of FES systems for stair climbing and descent, parallel bar measurements (from slanted bars) can be useful in determining modifications of muscle stimulation parameters.

The parallel bar system developed here has a force measurement range of 0–100 lbs, in each of the three component directions (F_y left-right; F_x front-back; F_z up-down). This was accomplished by modifying the design of standard parallel bar support posts. The strain gages were mounted on the support posts and the signals obtained from them were processed to extract the individual force components.

DESIGN

Figure 1 shows the block diagram of the parallel bar system. It consists of four upright supports, 12 strain gages on each support, two horizontal bars, 12 Wheatstone Bridges and 12 voltage amplifiers.*

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* Three-Component Force Measurement. D.N. Kuen, S.K. Lee, J. Mansour. Senior Project, Case Western Reserve University, 1985.

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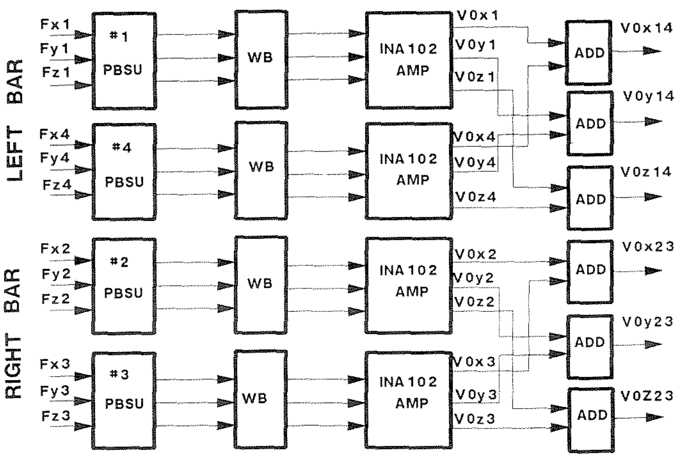

Figure 1.
Block diagram of the Parallel Bar System. Applied force components are sensed at the four parallel bar supports (PBSUs), and the voltages resulting from the strain gages are processed by the Wheatstone Bridges (WBs) and then amplified to obtain 12 combined output voltages corresponding to 12 force components. These are then combined (by the adder, ADD) to yield 6 net force signals (in the X, Y, and Z directions for each bar).

Parallel bar structure and sensor mounting

In order to obtain measurements of the desired forces, a mechanical modification of the parallel bar connections was carried out. Standard parallel bar connectors were replaced by pin joint connectors between the collars and support uprights. Thus, the bending moment along the Y-axis could be eliminated, and the horizontal angle of the bar could easily be adjusted. A special collar was used to connect the horizontal bars and the pin joints (**Figure 2**). Next, sensors were applied to the modified parallel bar. Forty-eight CEA-13-032UW-120 miniature strain gages (M-M Measurement Group, Inc., Raleigh, NC) were used. These foil strain gages vary in electrical resistance according to their deformation from force loading. To measure the three force components on each support upright, 12 strain gages were used in three Wheatstone Bridge arrangements (i.e., the total system consists of 12 Wheatstone Bridges—one for each force component). The use of four sensors for a Wheatstone Bridge is done to increase the force sensitivity. The gage mounting orientation is shown in **Figure 3**. In order to get pure outputs (especially in the X direction), the mounting surface of the pin joint must be parallel with the top notch of the upright. No friction should exist between the pin joints and uprights.

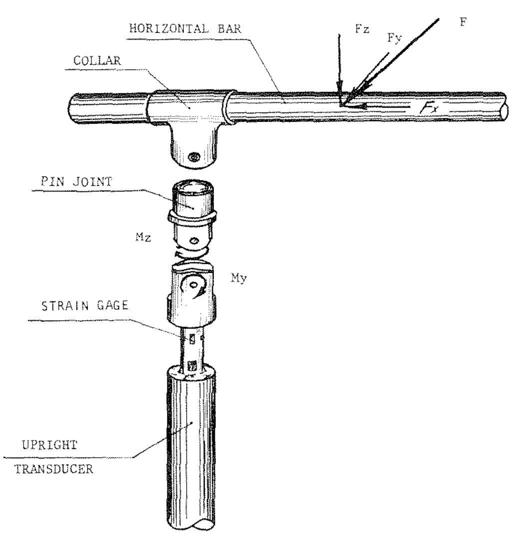

Figure 2.
Parallel bar perspective structure. It consists of horizontal bar, collar, pin joint, joint pin, and upright transducer. The pin joint is connected to the top notch of the upright with a pin, so it can rotate around the connecting pin. All 12 strain gages for three Wheatstone Bridges are mounted on the neck of the upright support.

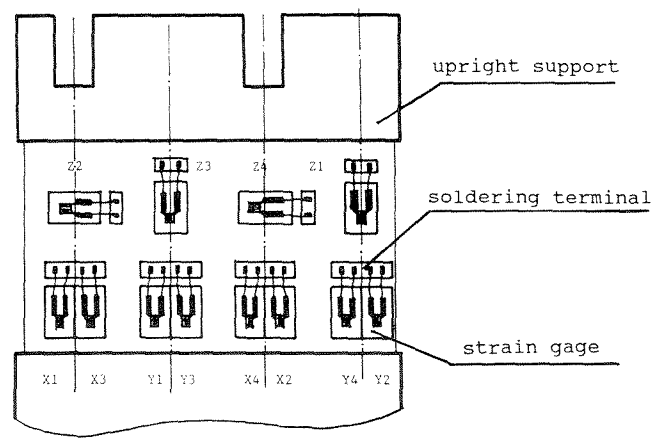

Figure 3.
In this diagram, the cylindrical surface of the upright has been developed on a plane. The upper part four gages are for the Wheatstone Bridge of the Z-axis (Z_2 and Z_4 are dummy gages), and the diagonally distributed eight gages are for X and Y axes.

Wheatstone Bridge and amplifier

The four strain gages in each Wheatstone Bridge convert resistance variations to differential voltages. They are mounted in such a way that R_1 and R_3 increase the strain gage resistance values (while R_2 and R_4 decrease the resistance values) caused by the exerted forces F_x and F_y. This allows for maximum sensitivity (**Figure 4**). The strain gage excitation voltages were chosen to be 2.20 V, following the guidelines in (4).

Here the gage grid area = 0.81 mm × 1.52 mm = 1.23 mm^2, and the upright material is heavy aluminum with a heat sink value of 2-5 watts/in^2. Twelve INA102G instrumentation amplifiers (Burr-Brown Corp., Tucson, AZ)

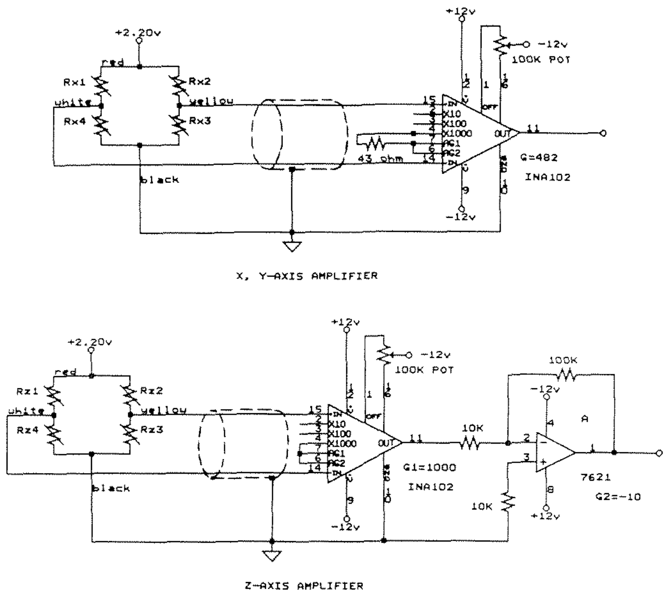

Figure 4.
Circuit diagrams of the Wheatstone Bridge and amplifiers. The different gains are obtained by the different connections of the INA102 amplifier. Since only two sensitive gages were used for the Z-axis, the large gain was selected for the INA102 amplifier, and the second amplifer stage 7621 was used.

were used to amplify the low-level bridge outputs to a level suitable for data collection by the laboratory computer system.

The front-back (F_x) and left-right forces (F_y) require four gages each. In principle, the up-down (F_z) bridge could be measured using only two strain gages. However, for convenience in the electronics, we used four gages here as well. Thus, the Z-axis amplifiers must have different gains than the other amplifiers (**Figure 4**).

The 12 force voltage signals are then processed to remove offset and to scale them according to the measured sensitivity data. This results in signals that correspond closely to the applied forces.

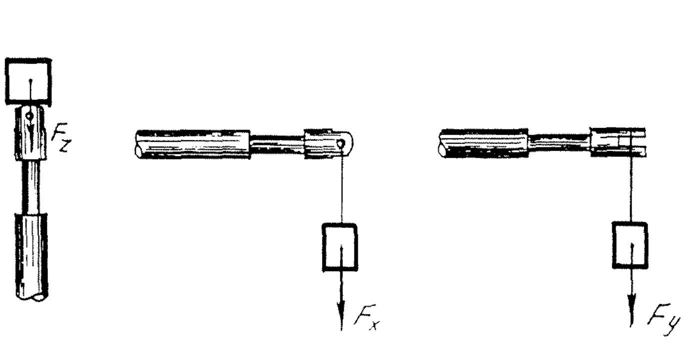

Figure 5.
Single bar calibration method. For the F_X and F_Y, the uprights are held in a horizontal position and different known weights are applied at the hole for connection. For the F_Z, the upright is held in a vertical position.

Force computations

The conversion of the raw voltages (from the Wheatstone Bridges) to force component measurements is based upon mechanical analysis of the system and the experimentally measured calibration data. The three components of a force on a parallel bar can be approximated as:

$$F_x = [EI/(S_g V_{in} C L_x)] V_{ox}$$
$$F_y = [EI/(S_g V_{in} C L_y)] V_{oy}$$
$$F_z = [2EA/(S_g V_{in})] V_{oz}$$

where E is the modulus of elasticity (Young's Modulus)

I is the moment of inertia
S_g is the strain gage factor (2.11 for this gage)
C is the radius of the upright
L_x is the strain gage's distance from the pin joint
L_y is the strain gage's distance from the center of the parallel bar
A is the cross sectional area of the upright
V_{in} is the Wheatstone Bridge excitation voltage
V_{ox} is the X axis amplifier's output
V_{oy} is the Y axis amplifier's output
V_{oz} is the Z axis amplifier's output

Thus, for each parallel bar we have:

$$F_{xi} = [EI/(S_g V_{in} C L_x)](V_{ox1}+V_{ox4})$$
$$F_{xr} = [EI/(S_g V_{in} C L_x)](V_{ox2}+V_{ox3})$$
$$F_{yi} = [EI/(S_g V_{in} C L_y)](V_{oy1}+V_{oy4})$$
$$F_{yr} = [EI/(S_g V_{in} C L_y)](V_{oy2}+V_{oy3})$$
$$Fz_i = [2EA/(S_g V_{in})](V_{oz1}+V_{oz4})$$
$$F_{zr} = [2EA/(S_g V_{in})](V_{oz2}+V_{oz3})$$

The above formulas comprise the components of the hand support forces exerted by the patient on the parallel bar system.

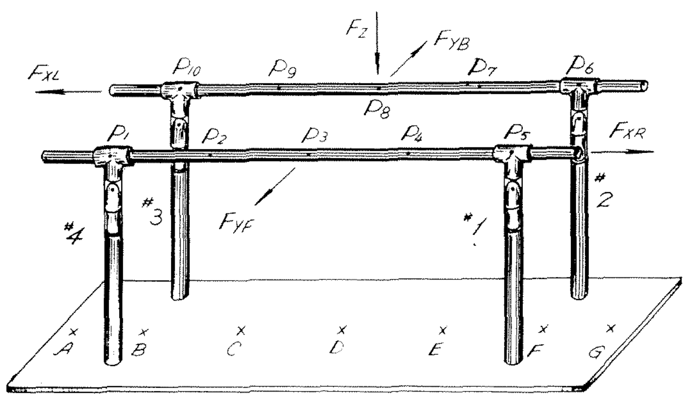

Figure 6.
Parallel bar calibration notation. Five positions are marked on each bar. The uprights #1 and #4 supported the left bar; the uprights #2 and #3 supported the right bar. In the calibration procedure, known weights were applied in the X, Y, and Z directions at each of the 10 positions.

Table 1.
Parallel Bar (PB) Calibration Data.

Applied Force (lbs)	10	20	30	40	50	Inter-cept	Slope (mv/lb)	Correlation coefficient
PBX_{l+}	255	494	743	993	1238	2.43	24.72	0.999978
PBX_{l-}	−250	−492	−730	−967	−1201	−7.57	−23.98	0.999924
PBY_{l+}	508	947	1372	1812	2255	71.1	43.59	0.999976
PBY_{l-}	−546	−1030	−1487	−1986	−2462	−65.8	−47.88	0.999933
PBZ_{l}	214	423	635	851	1068	−2.6	21.36	0.999968
PBX_{r+}	261	515	768	1025	1283	4.2	25.54	0.999991
PBX_{r-}	−258	−512	−765	−1017	−1268	−6.5	−25.25	0.999997
PBY_{r+}	490	933	1381	1808	2221	65.5	43.37	0.999861
PBY_{r-}	−482	−948	−1408	−1873	−2338	−18.7	−46.37	0.999998
PBZ_{r}	214	431	643	857	1073	0.40	21.44	0.999994

For each parallel bar and force direction, the average voltages (in mv), resulting from the five positions of applications, are shown for five different applied forces. Here l=left bar, r=right bar, "+" denotes positive force (as in **Figure 6**), and "−" is the negative force direction. X, Y, and Z indicate the force axis of application. The intercept, slope, and correlation coefficient for the resulting linear regression are also indicated.

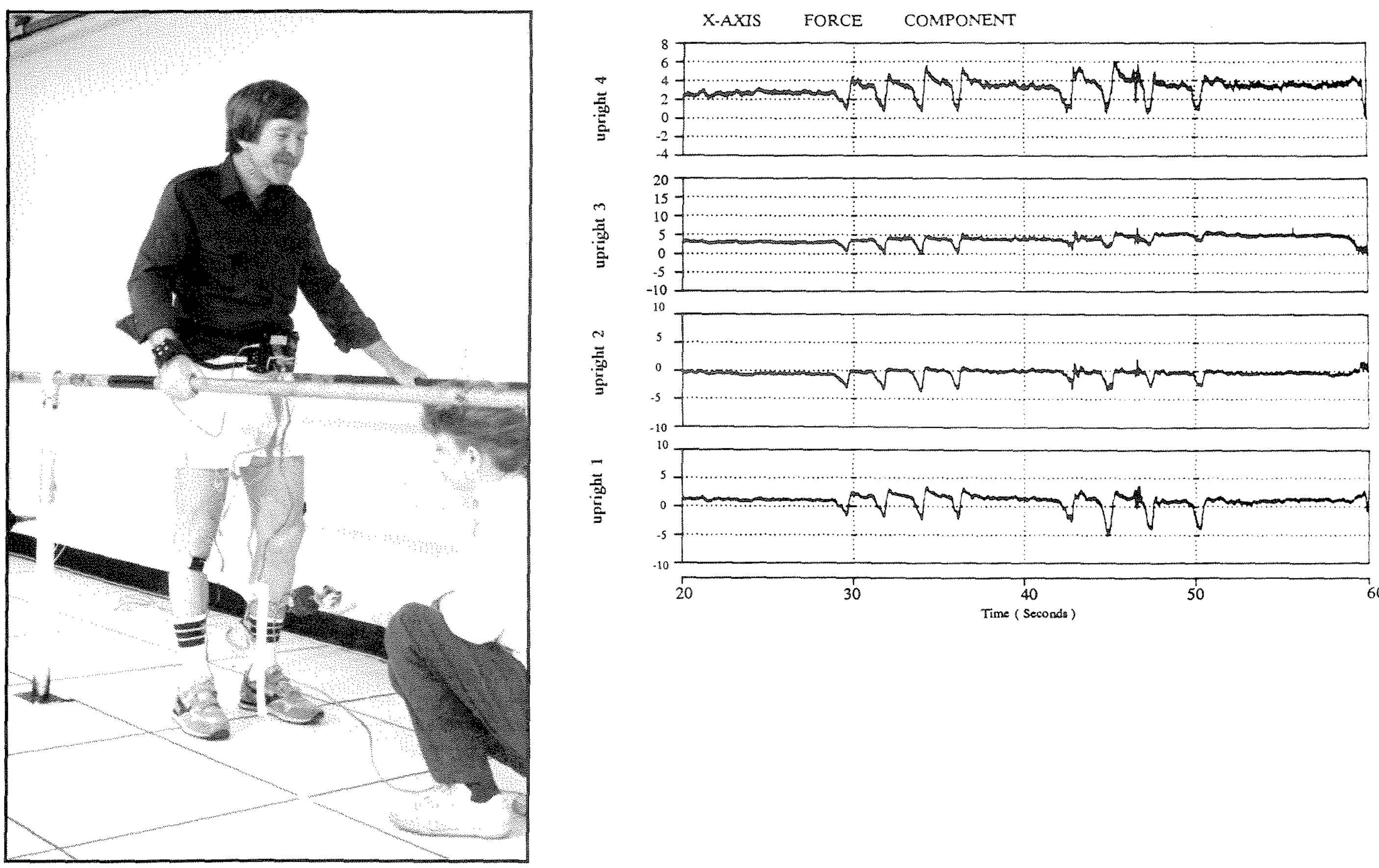

Figure 7a.
A stroke patient is standing using an FES system and has each hand on a parallel bar. A series of force disturbances were applied to the patient's right knee. Hand support force reaction data were collected from the parallel bars.

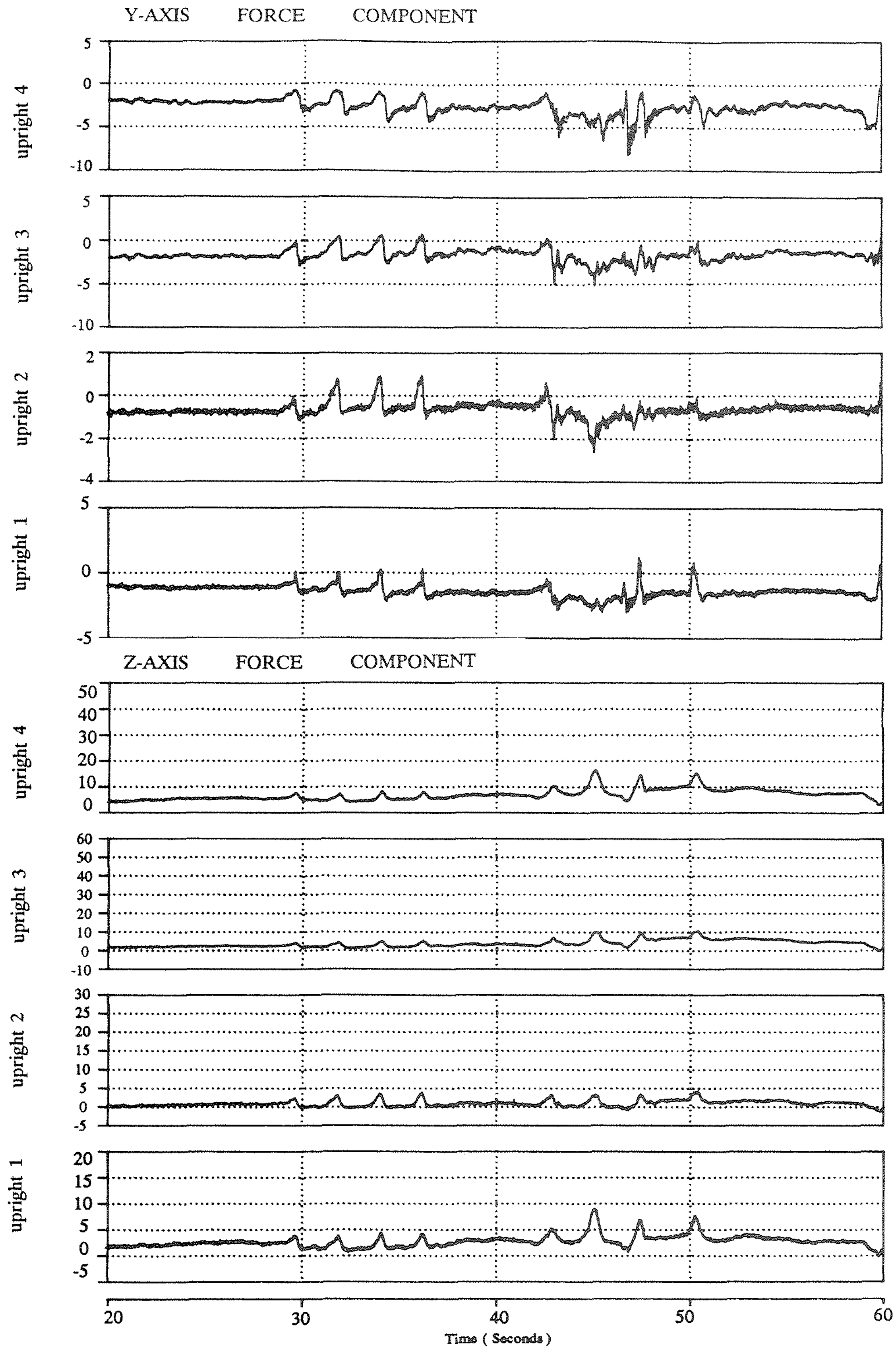

Figure 7b.
Patient HM's X, Y, Z-axis hand support force data (as defined in **Figure 6**). Each trace shows the magnitude of one force component in lbs.

Calibration

Prior to the use of this parallel bar system, it must be calibrated relative to known weights. There are two steps to this. The first step is single bar calibration. Each upright is calibrated by keeping it in a horizontal position, measuring the response to different known weights on each axis, and then calculating the sensitivity of each axis (see **Figure 5**). The second step in the calibration involves the parallel bars themselves. Each of the two parallel bars was first set in its normal position (see **Figure 6**). Then different known weights (from 0 to 50 lbs) were applied to each bar at five different positions, in each of the three directions.

A rope and pulley arrangement was used to do this along the X- and Y-axis directions. A load-cell was used to monitor the applied forces.

For each bar and each direction, the average of the five voltages (one for each location) was used to fit a static linear calibration curve (by linear regression). The following weights were used: 0 lbs, 10 lbs, 20 lbs, 30 lbs, 40 lbs, and 50 lbs. The linear fits (using A_{xj}, B_{xj}, A_{yj}, B_{yj}, A_{zj}, B_{zj}, j=1,2,3,4) were accurate to within 0.5 lbs over the 0–50 lbs range. (See **Table 1**.)

In operation, the 12 Wheatstone Bridge-produced voltages V_{oxj}, V_{oyj}, V_{ozj} (j=1,2,3,4) are processed in software, according to the calibration curves, to yield estimates of the 12 force components (three components on each upright) F_{xj}, F_{yj}, F_{zj}, j=1,2,3,4. For example, F_{x1} is estimated by:

$$F_{x1} = \frac{V_{ox1} - A_{x1}}{B_{x1}}$$

with parameters A_{x1}, B_{x1} given.

RESULTS

This parallel bar system has been used in the Cleveland VA Medical Center Gait Lab to measure hand support forces during standing, walking, and stair climbing. An example of the use of this parallel bar measurement system is shown in **Figure 7**. In this standing experiment, a stroke patient is standing using percutaneous intramuscular electrical stimulation. The traces of the parallel bar indicate the hand support forces (over time) that result when disturbances are applied to the patient's right knee (2). A second example of the use of the parallel bar system involved the evaluation of the closed-loop stimulation control of coronal plane hip angle during FNS stance (5). The patient, as shown in **Figure 8**, stood on forceplates with both hands on one parallel bar. The combined hand support forces acting on the bar (from both hands) were measured. A third use of the parallel bars is in functional neuromuscular stimulation (FNS) stair ascent and descent experiments, similar to those described by Chizeck *et al.* (6). In these experiments, each bar was used as a stair hand-railing, to collect three-dimensional force data on upper extremities. Recalibration is required for the sloping bars. An example of data from this experiment appears in **Figure 9**.

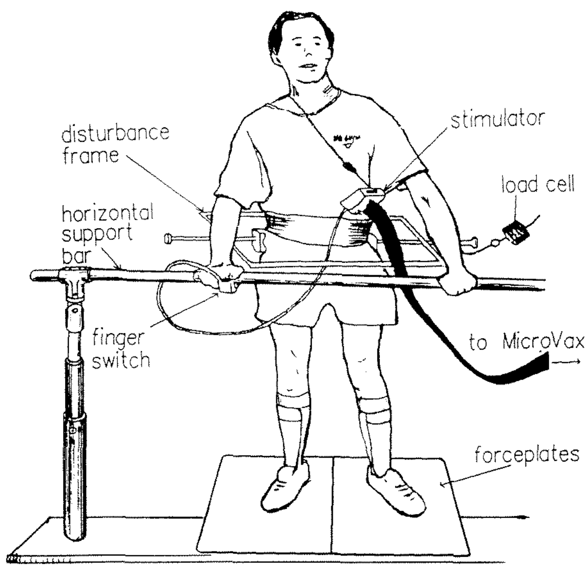

Figure 8.
Parallel bars being used in the evaluation of a feedback controller of coronal plane hip angle using FNS. The forceplates recorded the ground reaction force, and the parallel bar was used to collect the hand support force. Force disturbances were applied to cause the subject to bend at the hip in the coronal plane.

DISCUSSION

There are a number of potential error sources in this system. The gage mounting position is crucial. Deviations from specified absolute and relative locations can cause large cross-talk errors between the three axes of force measurements. A second source of error arises from the position averaging and the linear fits used in the calibration process. In calibration tests, the combination of these errors was found to be less than ± 0.5 lbs (in the 0–50 lb range). This error depends upon where the forces are applied. During experiments, the least error occurs if forces are applied to the middle of the parallel bars. A third error source is cross-talk between the three axis directions, and it completely depends on the gage mounting accuracy. This error was less than 5 percent in our trials (with known weights applied). This level of cross-talk noise has been achieved by the pin joint design and the sensor mounting arrangement.

When forces F_x, F_y, and F_z are applied by a subject's hands, there are a number of potential sources of coupling. The F_z force will cause the parallel bars to flex and the uprights to bend. The pin joint allows the parallel bar to rotate around the connecting pin. Therefore, if F_z is in the downward direction (on a single parallel bar), its two uprights are pushed apart; if F_z is in the upward direction, they are pulled together. Since a force F_z causes the two uprights to bend symmetrically (in opposite directions),

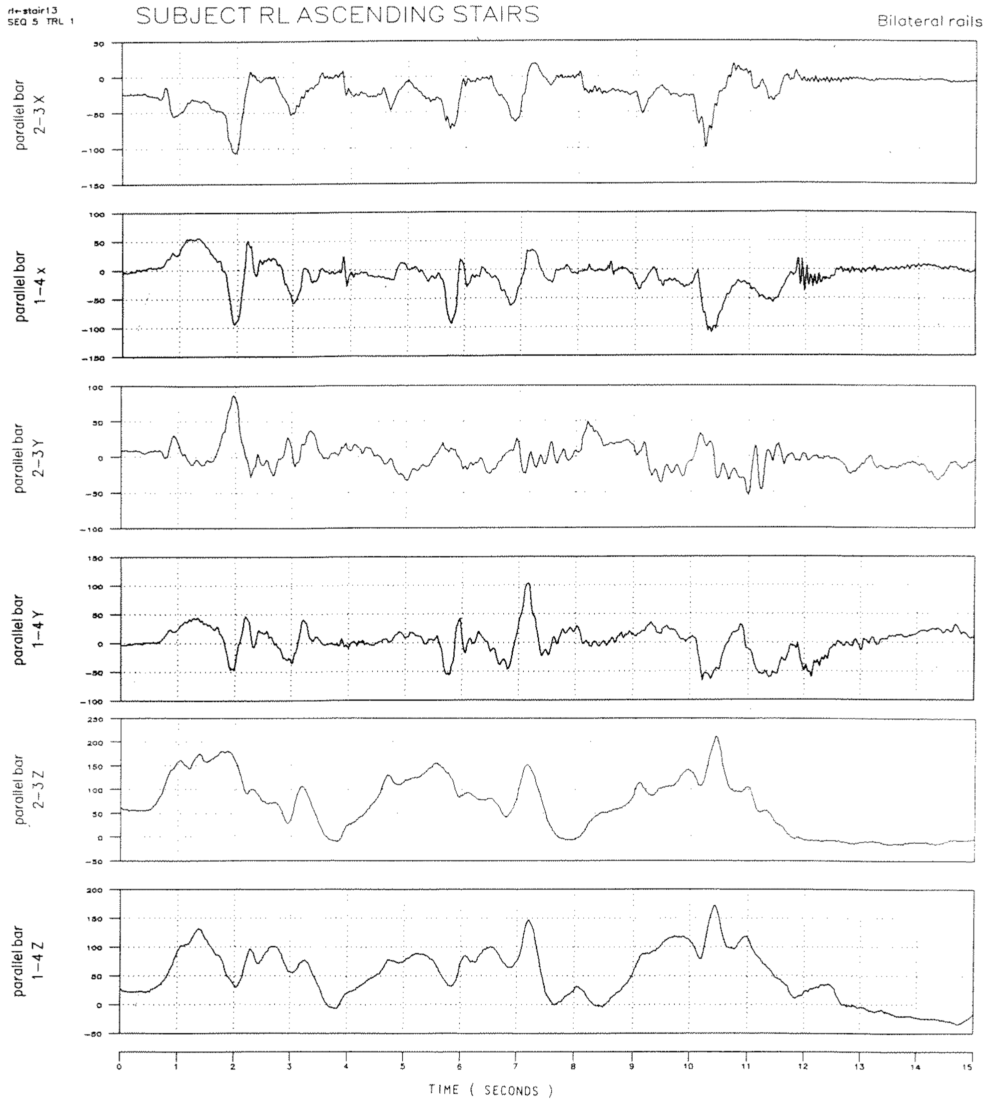

Figure 9.
Parallel bar hand support force data collected from a paraplegic patient during a stair-climbing experiment using FES. Each trace shows the sum of the forces acting on the supports of a parallel bar in newtons.

the false F_x output resulting from F_z in the two uprights is cancelled. In this situation, because the uprights are bent along the Y-axis transverse directions of the strain gage, F_z does not cause false outputs in the F_y measurements. The torsional loads about the X-axis, caused by subject's hand placement, can cause the uprights to bend about the X-axis, resulting in small F_y errors. However, this will not influence F_x measurements, due to the F_x sensor orienta-

Table 2.
Hysteresis Test (Z-axis).

	Increasing				Decreasing			
Applied Force (lbs)	**0**	**10**	**20**	**45**	**20**	**10**	**0**	
PBZ_r	−502	−287	−74	457	−76	−286	−497	mv
PBZ_r	−481	−266	−53	484	−51	−261	−474	mv

Two trials of forces applied to the middle of the right bar, in the Z direction are shown. Successive increases of forces (0, 10, 20, 45 lbs), and then decreases (45, 20, 10, 0), result in the signal levels shown (in mv).

tion. These torsional loads will deform the F_Z gages, but since one will be in extension and the other in compression, there will be virtually no effect on F_Z.

Hand rotational moments, about the Z-axis, will cause both of the uprights of a single bar to bend in opposite directions: the resulting F_y measurement errors cancel out. Hand rotation about the Y-axis only influences the Z-axis. Since one upright is given a downward force, while the other is given an upward force, these errors also cancel.

An F_y force can cause the parallel bars to flex along the Z-axis and exert moments on both uprights about the Z-axis. Since these moments are applied to all the gages in transverse directions, no significant F_x and F_z errors result. Likewise, an F_x force causes the uprights to bend about the Y-axis in the same direction: no significant F_y and F_z errors result.

Other possible error sources are hysteresis and effects of the electronics. From experimental observations (see **Table 2**), the system hysteresis is generally less than 1.5 percent. For best accuracy, the parallel bar system (bars and electronics) should be allowed to fully warm up before experiments begin.

The measurement errors described above could be reduced through the redesign of various mechanical components of the system. For example, the errors resulting from the bar flexing could be decreased by replacing the pin joints with angular contact ball bearing joints. Hysteresis and sensitivity could be improved by replacing the solid post by a hollow tube—this would increase the load on the strain gage elements. In order to reduce the location of the applied force error (and to simultaneously eliminate the need for half of the F_x strain gage bridges), a second ball bearing joint (in the same plane as the first) could be added to the posts at the end of each bar.

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REFERENCES

1. Abbas JJ, Chizeck HJ. FNS control system tuning and clinical ratings of performance. Proceedings of the 11th IEEE EBMS Conference, Seattle; 1989:1494-5.
2. Moynahan M. Characterization of paraplegic disturbance response during FNS standing [Thesis]. Case Western Reserve University, 1990.
3. Marsolais EB, Kobetic R. Development of a practical electrical stimulation system for restoring gait in the paralyzed patient. Clin Orthop Rel Res 1988;233:64-74.
4. Optimizing strain gauge excitation levels. Tech Note TN-502. Measurements Group, Inc., Raleigh, NC, 1979.
5. Abbas JJ, Chizeck HJ. Feedback control of coronal plane hip angle in paraplegic subjects using functional neuromuscular stimulation. IEEE Trans BME 1991;38(7):687-98.
6. Chizeck HJ, Kobetic R, Marsolais EB, Abbas JJ, Donner IH, Simon E. Control of functional neuromuscular stimulation systems for standing and locomotion in paraplegics. Proceedings of the IEEE, 1988;76(9):1155-65.