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Apparatus and procedures for the measurement of isokinetic, isometric and isotonic strength of the knee and elbow extensors and flexors, plantar flexors and hand grip muscles of the intact human body is presented. Special attention is given to immobilization of the proximal body segments and the biomechanical characteristics of joint and muscle groups being measured. Estimates of the reliability of the apparatus and procedure was found to be high indicating good ability to discriminate muscle strength among subjects on the selected muscle groups.

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Instrumentation and Techniques for the Measurement of Muscular Strength in the Human Body

by

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ABSTRACT

Apparatus and procedures for the measurement of isokinetic, isometric and isotonic strength of the knee and elbow extensors and flexors, plantar flexors and hand grip muscles of the intact human body are presented. Special attention was given to immobilization of the proximal body segments and the biomechanical characteristics of joint and muscle groups being measured. Estimates of the reliability of the apparatus and procedure was found to be high in most cases indicating good ability to discriminate muscle strength among subjects on the selected muscle groups.

INTRODUCTION

The need for quantitive assessment of muscle strength in both the clinical and athletic realms is well recognized. There have been a plethora of equipment, systems and methods that have been described to achieve this. Lovett and Martin's (24) spring balance test represents perhaps the first attempt to quantify the strength of selected muscle groups. In their system the strength was registered in a spring balance which was connected to a sling against which the subject exerted tension. The development of the cable tensiometer by Clarke and his associates (7,8,9) opened the possibility for a more reliable measurement. Since then a variety of strain gauge systems have been developed by various investigators (2,3,4,11,16,17,22,23,32,33,34).

The work of Beasley (3,4) is one of the most detailed and extensive ones in the area of muscular strength measurement. Interpolating strain gauges between the extremity to be tested and the examiners hand, he attempted to correlate the subjective grading given by the examiner and the actual strain gauge recording. His study served to point out the poor sensitivity of the manual muscle test. The values he gathered in large population screenings are still used as standards. Unfortunately, most of his data has not been published.

Most of the methods mentioned above attempted to measure the strength in an isometric mode. DeLorme (12,13) has described and isotonic method and more recently, Moffroid and her coworkers (25) as well as Molnar and Alexander (1,26,27), have attempted to measure muscle strength utilizing an isokinetic dynamometer.

The major problem in the establishment of a muscle strength (ergographic) laboratory is the lack of commercially available instruments capable of measuring strength in a precise and reproducible manner. Most of the commercially available ergometers are far from adequate, particularly in respect to their disregard for the functional position of the body segments during exercise. This is illustrated in a typical, commercially available hand grip ergometer which totally ignores the normal 15° of ulnar deviation of the functioning hand. In the intact human subject the muscle contraction causes rotation around an axis at the joint. The instantaneous direction of motion, at any point, is tangential to the arc of motion and perpendicular to its radius. The measurement of muscular strength is done by measuring the opposing force which is also acting tangential to the arc of motion. The measurement obtained is the tangent force reaction. It is reasonable to assume that the tangent force reaction should be measured at the distal end of the lever directly affected by the muscle group whose strength is being measured.

With very few exceptions (34) many of the ergometers which are commonly used for measuring quantitative muscle strength present the even more serious handicap of inadequate immobilization of the body segments. Proper immobilization offers a standard way for positioning subjects and if carefully chosen, will also offer the opportunity to exert tension with the optimum mechanical advantage and prevent the occurrence of synkinetic patterns.

Given these two conditions, the nature of the measurement and the angle of insertion, it is obvious that in order to obtain accurate, reliable and reproducible results the position of the extremity has to be standardized and the proximal segments immobilized in a specific and reproducible way. When these factors are not taken into account extraneous variables may complicate the measurement. For example, some devices used for elbow extension and flexion measurement use the hand as the point of subject machine coupling. This introduces the positioning and relative strengths of the wrist and fingers into the measurement, increasing the variability and decreasing the reliability of the test.

A critical review of the methodology presented in most articles on strength testing showed an impressive disregard for standardization of their testing methods. Testing was done without any regard for proper immobilization (1,11,25,33) although some investigators verbally asked subjects to refrain from associated movements (30). Despite the importance of standardizing the instructions given to the subject (6,20) many studies did not report this. Additionally, the criterion score used as a strength measure was often not given (1,26,30).

Thus it was deemed necessary to develop apparatus and a methodology that would take into consideration the above mentioned factors. As an initial step to this purpose, six functional muscle groups were chosen for examination: the knee extensors and flexors, elbow extensors and flexors, plantar flexors and hand grip. The criteria for selection of these muscle groups included: muscles used in commonly encountered tasks, the possibility of good intercorrelation (extensor and flexor groups), ease of accessibility, and the possibility of good stabilization so as to minimize the involvement of synkinetic muscle patterns. Techniques for isokinetic, isometric and isotonic strength measurement were developed.

The purpose of this paper is to describe the apparatus, methodology and reliability of a three year effort to measure the maximum voluntary strength of selected muscle groups in the intact human subject.

EQUIPMENT DESCRIPTION

KNEE AND ELBOW APPARATUS

SUBJECT SEATING ARRANGEMENT. Figures 1 and 2 show the subject seating arrangement for knee extension and flexion and elbow extension and flexion, respectively. In both cases a heavy wooden chair (Lumex Corp., Cybex

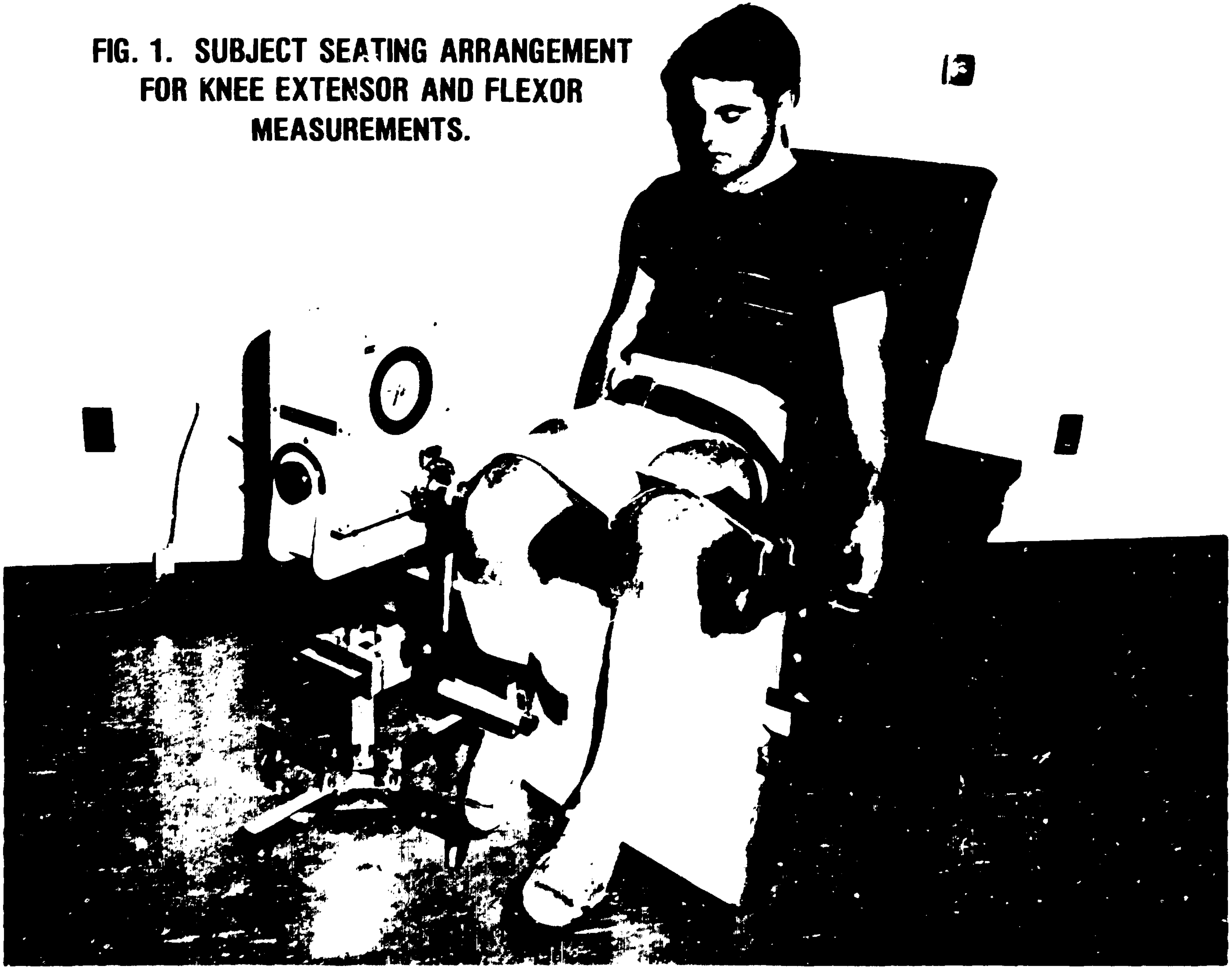


FIG. 1. SUBJECT SEATING ARRANGEMENT FOR KNEE EXTENSOR AND FLEXOR MEASUREMENTS.

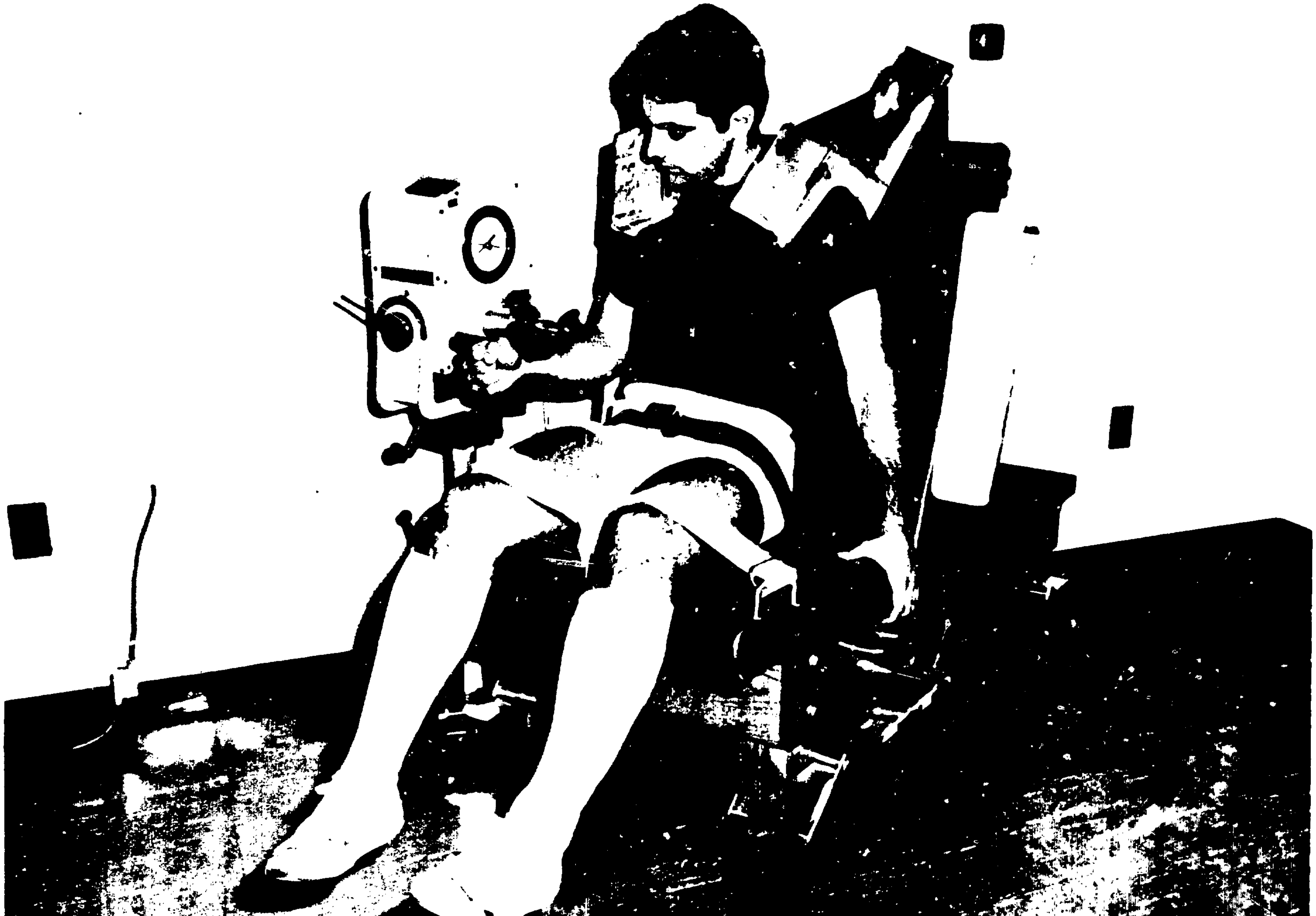


FIG. 2. SUBJECT SEATING ARRANGEMENT FOR [redacted] EXTENSOR AND FLEXOR MEASUREMENTS.

Division, Bay Shore, New York) with an adjustable back inclination was modified. The back of the chair was fixed at a 105° angle. For knee extension and flexion measurements a 3 inch (7.62 cm) nylon strap was attached to the back of the chair using an 8 inch (20.32 cm) rail to allow upward and downward adjustment. This strap was used to immobilize the thoriac region. A 2 inch (5.08 cm) nylon adjustable seat belt was also attached to the seat close to the hinge at the back of the chair. Similar straps were attached to the anterior edge of the seat to immobilize the thighs immediately proximal to the femoral condyles. An additional strap was anchored anteriorly, medial to the exercised leg at the level of the femoral condyles passing proximally over the thigh, attaching to the ipsilateral seat belt attachment. The chair utilized for elbow extension and flexion measurements contained a 3 x 18 inch (7.62 x 45.72 cm) wooden triangular wedge which served as an arm rest. The angle of the chair back (105°) complemented with the one of the wedge (15°) offered a 90° vertical support for the arm. The thigh straps and seat belt were identical to the knee chair. Both chairs could be used for measurement of the right or left body segments.

SHOULDER RESTRAINT UNITS. Figure 3 illustrates the shoulder restraint units. These were utilized for elbow extensor and flexor measures in order to immobilize the shoulders. A pair of railings (A) were attached to the back of the chairs and served as the main anchor for these units. The posterior portion (B) consisted of a triangular shaped stainless steel frame which projected anteriorly over the top of the chair back. This piece anchored to the rails at the rear of the chair allowing lateral and rotational adjustment. A second triangular frame (C) extended downward, parallel to the back of the chair. This was fitted between a set of guide rails on the projection of the posterior component to allow upward and downward adjustment. A wooden block (D) was contoured to fit the shoulder. Based on a large sample of subjects it was found necessary to

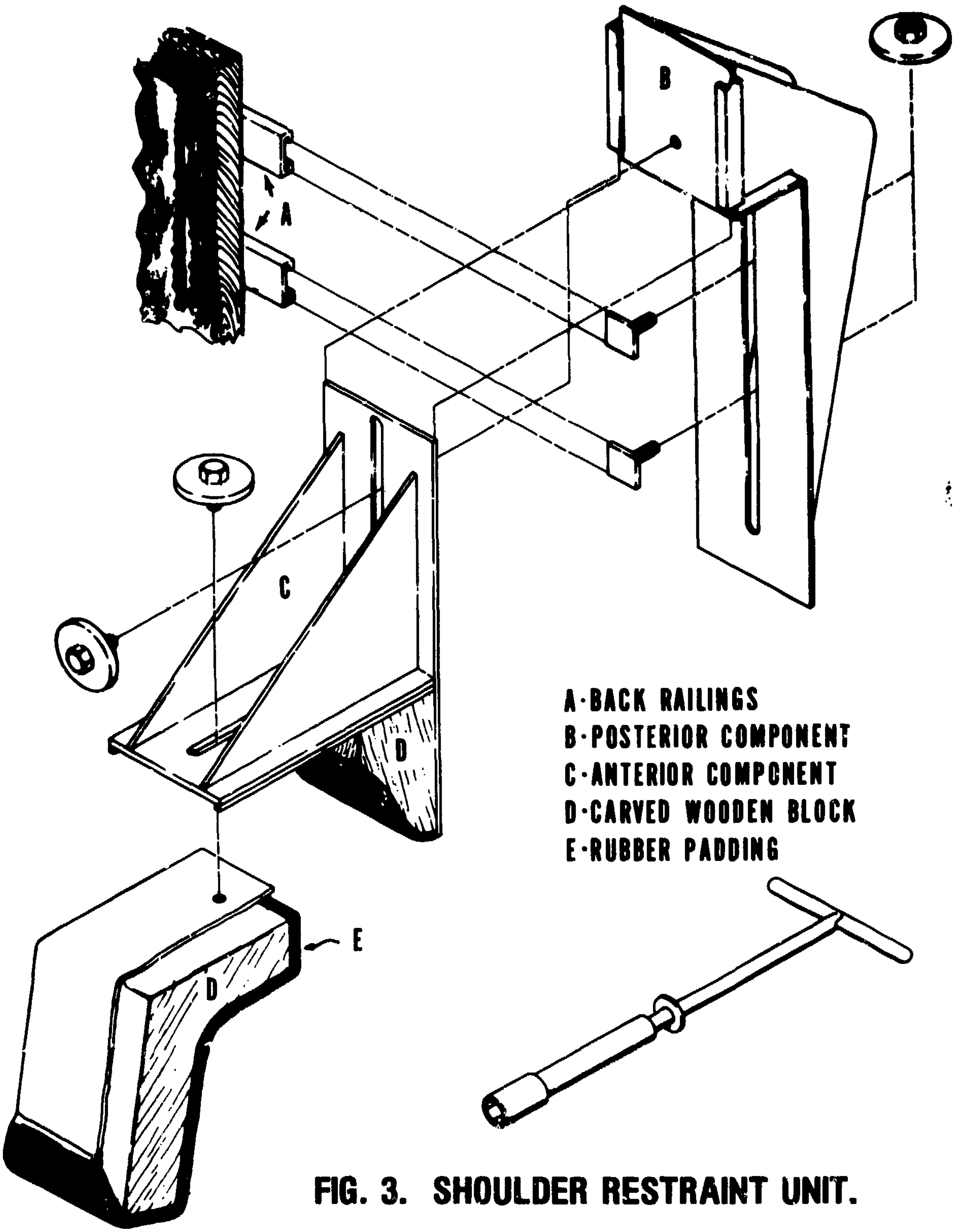


FIG. 3. SHOULDER RESTRAINT UNIT.

cut the block to accommodate shoulders of varying sizes. The block was fitted to the frame in two pieces with the anterior part attached to a metal frame allowing adjustment as shown. The wooden pieces were covered with 0.25 inch (0.63 cm) hard rubber (E) to provide optimal comfort with minimal padding.

ISOMETRIC - ISOKINETIC TORQUE UNITS. The Cybex II dynamometer (Cybex Division, Lumex Corp., Bay Shore, New York) has the capability of measuring either isometric torque or isokinetic torque at various contraction velocities (18). Thus this dynamometer was considered extremely useful for measuring static and dynamic muscular strength. It was found necessary to apply some modifications to the units. All the horizontal and vertical adjustments of the base and anchors were inscribed with marks measuring to the nearest 0.25 inch (0.63 cm). All the points of adjustment were fitted with lock screws to prevent any movement and loss of proper alignment. The coupling of the lever arm to the axis of the ergometer was found to be a source of spurious movement. Two lock screws were fitted in the hub of the lever arm preventing any movement at this joint. The lever arm was also inscribed and marked to the nearest 0.25 inch (0.63 cm) from the center of the axis. Each one of the above adjustments could be recorded for a subject and used if he was tested again.

ISOTONIC TORQUE UNITS. The isotonic torque units were built to allow for testing of isotonic strength and to employ a range of motion that was identical with the isometric - isokinetic torque units described above. A two lever system was designed and built as illustrated in figure 4. The subject lever arm (A) was converted into a cantilever system using two BLH Electronics (Waltham, MA) SR-4, constantan foil strain gauges which were attached to the bar at the point of maximal deflection close to the axis (B). The strain gauges were attached to the bar with a neoprene patch and covered with a rubber

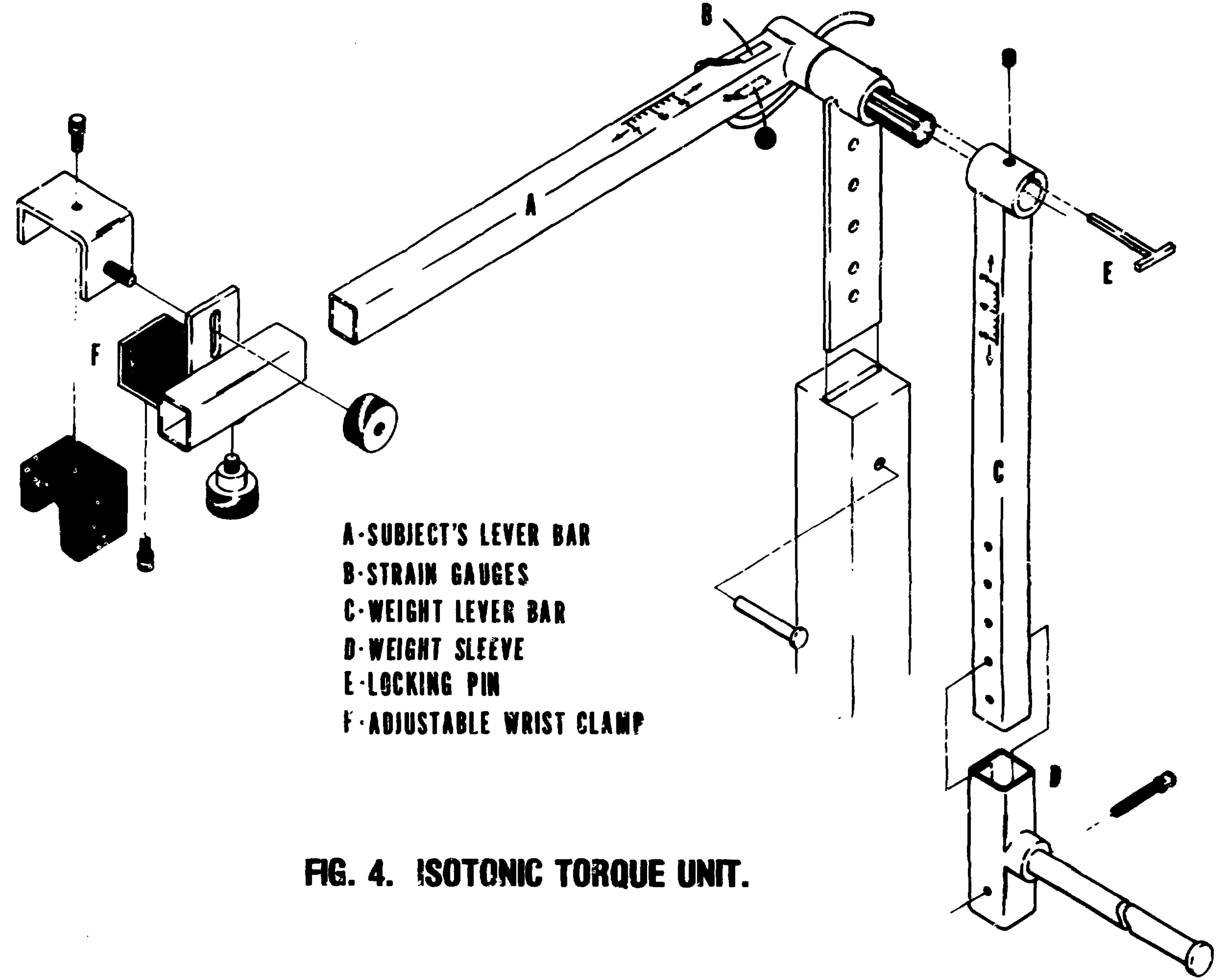


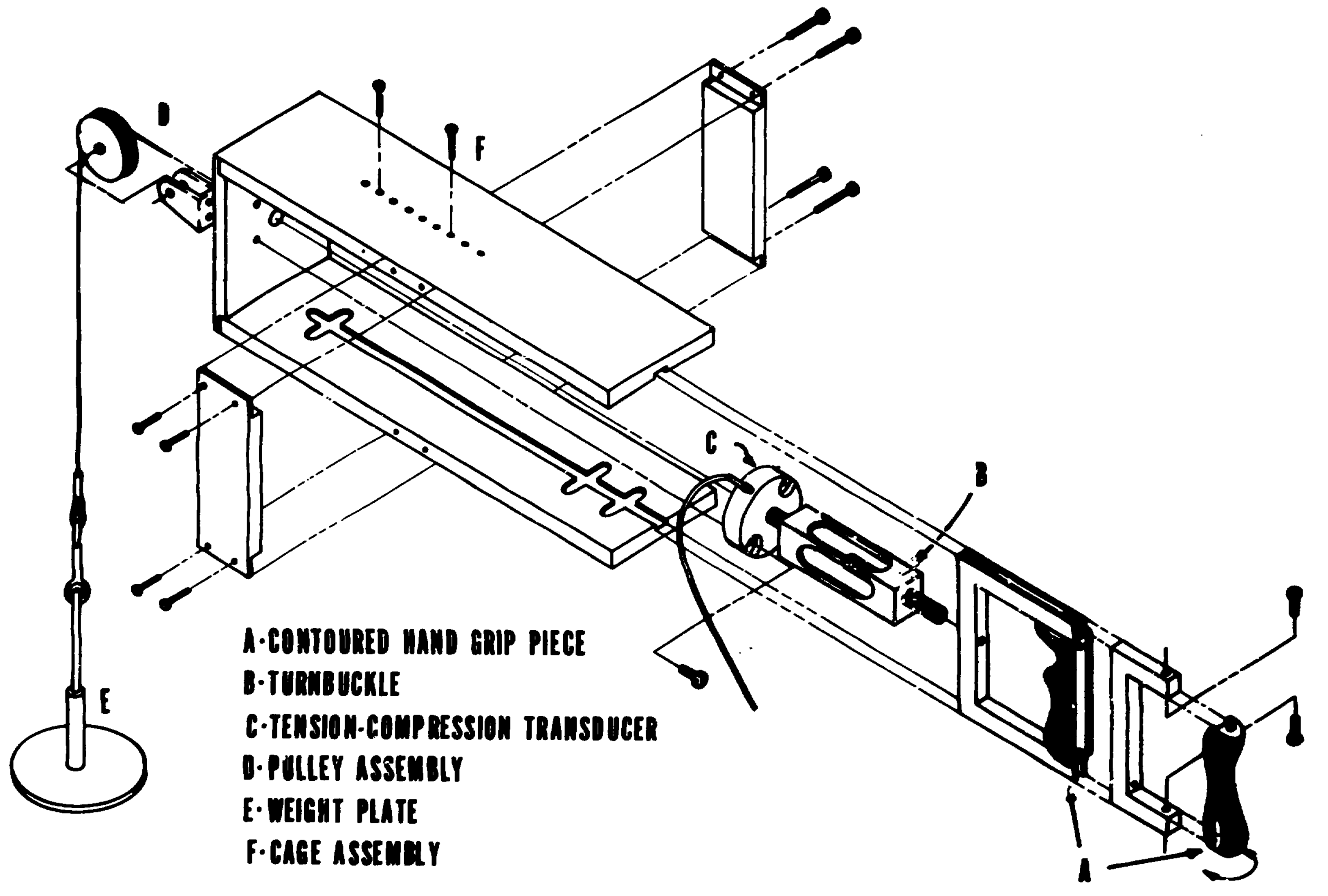
FIG. 4. ISOTONIC TORQUE UNIT.

polymer (BLH Electronics Barrier E). These were coupled with resistors chosen so as to have an equal resistive value as the strain gauges. The resistors and strain-gauges were mounted on the bar and wired into a wheatstone bridge.

A weight bar (C) was fitted to a square sleeve (D) which allowed positioning of the load to accomplish a predetermined lever length. Its position was secured by means of a lock screw at the axis. This weight bar could be loaded with weights (in 1 kg. increments) to determine a subject's one repetion maximum or for repeated submaximal contractions. Both the subject lever bar and the weight lever bar were inscribed with 0.25 inch (0.63 cm) incremental marks from the center of the axis of rotation to the edge of the lever bars. A number of different angles were allowed between the two lever systems controlled by a locking pen (E).

SUBJECT - MACHINE COUPLINGS. The subject - machine couplings were applied to the distal end of the body segment directly affected by the muscle group being tested: the distal forearm or the distal leg. For testing elbow extension and flexion an adjustable stainless steel cuff, identical to the one seen in Figure 4 (F), was designed and fitted with carved wooden blocks to conform the contour of the wrist. The interior surfaces were covered with 0.25 inch (0.63 cm) hard rubber. Three sets of these carved wooden blocks were manufactured which could easily be removed and replaced in order to accommodate wrists of varying sizes. A similar stainless steel cuff was built to conform to the distal leg. This ankle cuff followed the design of the Cybex II (Cybex Division, Lumex Corp. Bay Shore, New York) leg cuff.

For the testing of elbow extension and flexion the forearm was fixed in a midposition between supination and pronation. The wrist cuff was adjusted for each subject to a position where the distal edge of the cuff layed in juxtaposition



A·CONTOURED HAND GRIP PIECE
B·TURNBUCKLE
C·TENSION-COMPRESSION TRANSDUCER
D·PULLEY ASSEMBLY
E·WEIGHT PLATE
F·CAGE ASSEMBLY

FIG. 5. ISOTONIC HAND GRIP ERGOMETER.

to the base of the first metacarpal bone. For the testing of knee extension and flexion the distal edge of the ankle cuff was positioned 1 inch (2.54 cm) proximal to the malleoli.

HAND GRIP AND PLANTAR FLEXOR ERGOMETERS

The isometric hand grip ergometer and the testing protocol used is the one developed by Mundale (28,29). His design takes into consideration many of the problems already mentioned. The grip pieces were contoured to conform with the contour of the hand and fingers in a grip position. Their placement was such that it accounted for the 15° of ulnar deviation of the functional hand, accomplishing a comfortable subject machine coupling. A turnbuckle allowed adjustments for hands of different sizes. The ergometer was adjusted so as to produce an angle of 150° at the third metacarpalphalangeal joint and 110° at the proximal interphalangeal joint of the third finger. Mundale's (28) hand grip studies at multiple angle combinations identified this combination as the one which produced the maximal grip output. The grip strength was transferred through the turnbuckle to a BLH Electronics C2M1 tension compression transducer with a range of zero to 225 kg and an accuracy of 0.5%.

The basic design of the grip ergometer was modified to allow isotonic testing also. This was accomplished by mounting the transducer and the turnbuckle to a stainless steel cable using a tension adapter (BLH Electronics). The cable was passed over a pulley and connected to a weight plate. The excursion of the anterior grip piece was controlled by lock screw. This isotonic unit is illustrated in Figure 5. The isometric unit is identical except the pulley and weight plate was eliminated, the turnbuckle extended and the transducer attached to the rear of the cage assembly.

The isometric plantar flexor ergometer used is a modification of the

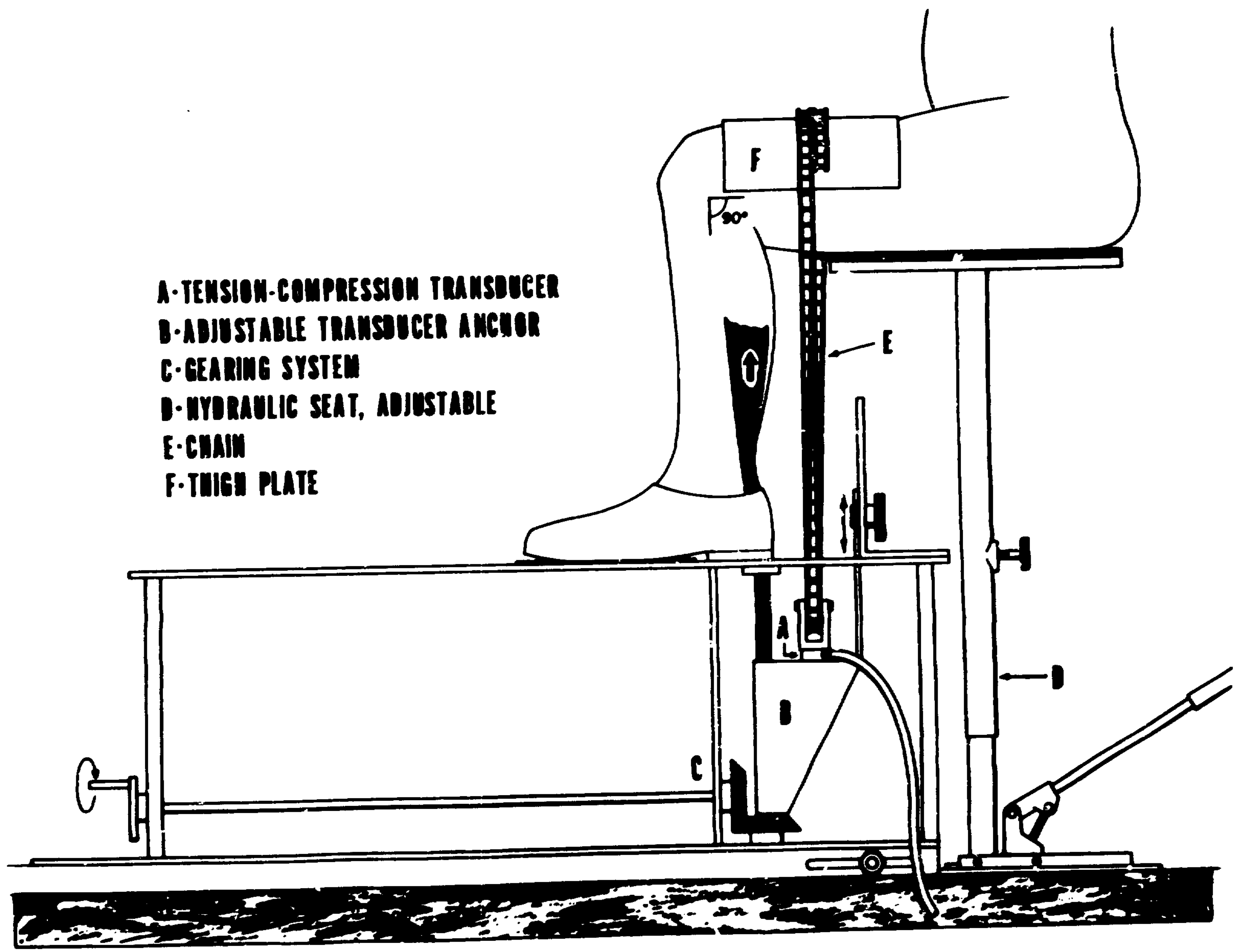


FIG. 6. PLANTAR FLEXOR ERGOMETER.

originial Beasley design (4) and is illustrated in Figure 6. A platform of 0.75 inch (1.91 cm) thick aluminum was constructed. A BLH Electronics U2M1 tension compression transducer (A) with a zero to 455 kg range was mounted into a metal frame (B) underneath the platform. The metal frame with transducer was mounted into a 2 inch (5.90 cm) threaded axle which attached to a gear system (C). This allowed vertical adjustment. The axle of the transducer was connected to a 2 inch (5.08 cm) diameter pulley.

A hydraulic lift served as the adjustable seat (D) for the subject. The seat was adjusted until the angle at the knee was 90°. With the shoe of the subject over a high friction non compressible rubber mat attached to the platform, a bicycle chain (E) was threaded through the pulley connected to the transducer. Both sides of the chain were passed over the distal thigh of the subject. The chain was secured on the blunted spikes of a stainless steel thigh cuff (F). The final adjustment was accomplished by raising and lowering of the transducer with the cranking mechanism attached to the gear system.

ELECTRONIC PROCESSING OF THE SIGNALS

Three major parameters were of interest: torque (or force), peak rate of torque (or force) development and integrated torque (or force). The Cybex II dynamometers produced a direct output of torque.

The electronic signals of the isotonic torque units were fed into a low level DC preamplifier of a 10 channel Polygraph (Model 7, Grass Instrument Co., Quincy, MA), and printed out on paper as torque. From the DC preamplifier, the signal was fed into an offset driver with a zero to 5V span which was then fed into an integrating preamplifier, (Grass Instrument Co. model 7P10B) differentiating preamplifier (Grass Instrument Co. model 7P20B) and a meter relay.

The meter relay was a voltmeter that could be adjusted such that its full span was equal to the subjects maximal voluntary contraction (MVC). Two sentinel needles then narrowed the level of contraction to $\pm$ 1% of any predetermined percentage MVC to be exerted. Any under or overshoot was detected by the meter relay and sentinel lights activated. A subject could thus be asked to maintain a certain percentage of their MVC and an endurance measure obtained.

A second 10 channel polygraph (Hewlett Packard Co., Waltham, MA., Model 7700 series) received the input of the Cybex II dynamometers. The signals were fed into a medium gain amplifier (Hewlett Packard model 8802A) to obtain torque. These signals were then relayed to a derivative computer (Hewlett Packard model 8814A) and an integrator (Hewlett Packard model 8815A) to obtain the peak rate of torque development and integrated torque. A meter relay was connected to this system as with the isotonic units. The four torque signals (two from each polygraph) were fed into a Hewlett Packard model 3520A magnetic tape recorder and simultaneously displayed on a Hewlett Packard model 760 monitor oscilloscope.

The outputs of the hand grip and plantar flexor transducers were fed into the carrier amplifier (Hewlett Packard model 8805B) of a Hewlett Packard model 7702B oscillographic recording system and displayed on a paper read out as force. A measure of integrated force or the peak rate of force development could be obtained using a Hewlett Packard model 8815A or a Hewlett Packard model 8814A.

METHODOLOGY

When a subject arrived in the testing area he was briefed as to the purpose of the testing by the investigator and was allowed to ask questions and visually examine the equipment. The technician seated the subject in the appropriate apparatus and set the immobilization devices in place. The appropriate angles of the body segments being measured were adjusted. The position of the vertical and horizontal adjustments, length of the lever arm and angle of the involved body segment were recorded. Prior to all testing the subjects were offered the opportunity to exert a submaximal contraction.

Kroerner and Howard (20) and Caldwell et al. (6) have pointed out that the manner in which the subject is instructed to exert force can have a marked effect on the value obtained. Thus, the instructions and vocabulary to be used was written and the technicians trained to offer them in a specific way.

In all cases, the subject was informed as to the purpose of the experiment. For isometric testing the subject was informed that the bar would not move. He was told to build up to his maximal force as rapidly as possible and hold it until told to stop (4-5 sec). For isokinetic testing subjects were asked to move the bar "as hard and as fast as possible," completing the entire range of motion. For isotonic testing the subject was instructed to move the weights through the entire range of motion. For both isometric and isokinetic testing the subject was given two or three submaximal contractions before the first trial. For isotonic testing the subject contracted against one or two submaximal loads before the first trial.

RELIABILITY AND CRITERION SCORE DETERMINATION

The reliability of the equipment and methods was a critical consideration. If the apparatus or test procedures could not give repeatable, verifiable results, any data collected would be of questionable value. Another factor of consideration was the selection of a criterion score that could be utilized as a measure of muscle strength. The literature revealed that two approaches were commonly applied: use either the maximal value of a series of trials or the mean of a series of trials.

In order to estimate reliability, intraclass correlation techniques were used because of their numerous advantages over the product moment correlation approach (18,31). For the present purposes, the error variances associated with trials and days were chosen for examination. These two variables were considered important because the apparatus and test procedures were expected to be involved in sampling of various populations for normative data and for use in pre-post testing.

METHOD

For test 1, 12 normal laboratory personnel (eight males and four females) volunteered. Their average age, height and weight ($\pm$SD) was 24.71 ($\pm$3.87) years, 171.71 ($\pm$11.85) cm, and 70.43 ($\pm$13.17) kg, respectively. Subjects were tested for knee extension (KE) and flexion (KF), plantar flexion (PF), elbow extension (EE) and flexion (EF) and hand grip (HG) using the equipment and methods described above. Individuals were tested one day on three muscle groups then returned three days later for a retest. They returned at irregular intervals for testing on the other three muscle groups and were again retested three days later. Opposing muscle groups (extensors and flexors) were always tested in the same session. For each muscle group, three isometric contractions were given on both days with two minutes rest between contractions. Subjects were instructed to build to their maximal strength in about one to two seconds and hold it until told to relax (about 4 to 5 sec.).

For test 2, 13 normal, healthy male volunteer soliders served as subjects. Their age, height and weight ($\pm$SD) was 21.8 ($\pm$2.2) years, 179.9 ($\pm$9.3) cm, and 73.2 ($\pm$10.4) kg, respectively. Subjects were tested on two consecutive days using the apparatus and techniques described above. On each day, three contractions were given on the KE and EF at isokinetic velocities of both 36°/sec and

180^{o}/sec. Two isometric contraction were also given on each muscle group. At least 30 sec of rest was given between each contraction. On each day, subjects finished one muscle group before starting the next, completing the slow velocity, fast velocity and isometric tests in that order. The isometric instructions were identical to those given in test 1. When performing isokinetically, subjects were instructed to "move the bar as hard and as fast as possible" completing the entire range of motion.

RESULTS AND DISCUSSION

The problem of the selection of a criterion score is highly related to reliability estimation. Reliability theory assumes that the scores obtained are all measures of the same parameter and that the error components are random, uncorrelated and independent (14,31). In order to test this latter assumption, Kroll (18) advises a repeated measures analysis of variances ANOVA while Liba (21) suggests a trend analysis. In either case, if the differences are not significant, the assumption of random and uncorrelated error variances is tenable and reliability estimation may proceed. If these assumptions prove valid, Kroll (18), Baumgartner (5), and Henry (15) suggest using the mean of all available trials as the criterion score.

A repeated measures ANOVA was performed on the six available trials for each muscle group. Table 1 shows a trend for higher scores for the KE and EF on test 1 but a trend for lower scores in all parameters on in test 2. However, the only statistically significant score change occurred in the KE at 36^{o}/sec in test 2. Since the tests were given on two consecutive days in test 2, it may be reasonable to suggest that the score decrement was due to a fatigue effect. However, with the possible exception of the KE at 36^{o}/sec, the data suggests that the criterion strength score for any particular muscle group should be the mean of all available trials.

TABLE 1. Isometric and Isokinetic Values for Various Muscle Groups (all Values in Newton Meters of Torque Except for the Plantar Flexors and Hand Grip Which are in Kilograms of Force)

	DAYS		DAY 1			DAY 2			F-VALUE
	TRIALS		1	2	3	1	2	3	
TEST 1 (N=12)	KE ISOM	MEAN	215.4	218.3	218.4	230.7	227.4	231.3	2.33
		SD	58.7	67.4	64.5	72.0	65.2	69.8	
	KF ISOM	MEAN	140.9	143.7	146.2	145.3	146.5	148.1	1.69
		SD	43.5	44.8	42.0	50.2	44.4	49.5	
	PF ISOM	MEAN	125.1	130.3	130.7	129.1	133.3	133.8	0.90
		SD	17.7	20.7	20.4	19.0	27.0	25.9	
	EE ISOM	MEAN	61.3	64.7	61.3	63.7	61.7	63.5	0.58
		SD	17.3	20.4	20.3	23.0	22.7	23.4	
	EF ISOM	MEAN	60.9	62.7	60.7	65.3	65.8	65.3	2.99
		SD	18.8	19.4	18.0	20.7	20.1	20.6	
	HG ISOM	MEAN	47.5	46.9	48.2	48.1	47.0	48.8	0.62
		SD	13.4	13.2	13.5	12.8	11.8	12.8	
TEST 2 (N=13)	KE ISOM	MEAN	261.9	261.0		263.9	263.9		2.28
		SD	26.6	26.5		36.2	35.8		
	KE 36°/sec	MEAN	249.8	252.6	255.9	228.2	230.3	234.4	12.29*
		SD	21.2	23.[illegible]	25.7	28.2	31.2	29.8	
	K[illegible] 180°/sec	MEAN	138.4	140.9	139.1	137.7	137.4	137.2	0.54
		SD	11.2	11.3	11.4	16.1	17.0	15.5	
	EF ISOM	MEAN	72.4	71.8		68.1	70.3		1.86
		SD	8.5	7.4		7.4	7.6		
	EF 36°/sec	MEAN	57.3	56.4	56.2	54.9	54.6	53.7	2.62
		SD	6.3	7.1	7.4	7.1	7.4	8.0	
	EF 180°/sec	MEAN	42.5	42.5	41.7	38.5	39.0	38.8	2.91
		SD	6.0	5.5	5.5	4.6	5.2	5.4	

*Statistically significant, $p < .05$

Reliability was estimated using a two way nested ANOVA as described by Safrit (24) and Feldt and McKee (10). The results are shown in Table 2. Since the F-value for the KE at 36°/sec was statistically significant, it is not possible to interpret the reliability of this parameter (18,24) although it is very low. It is interesting to note that in both tests 1 and 2 the isometric measures show somewhat higher reliability than the isokinetic measures with the exception of the PF. In all cases, the largest portion of the total variance is among subjects indicating the tests can discriminate strength among subjects. The trial-to-trial variations are small while the day-to-day variations make up most of the error variance. The larger day-to-day variance may be due to biologic variations in the subject and/or slight differences in the subject-machine coupling. Reliability estimates are acceptably high on all parameters except the PF and KE at 36°/sec. The reasons for this were not readily apparant but suggests caution in interpretation of any results obtained from these tests until the reliability is improved.

TABLE 2. Reliability Estimates and Portions of Total Variance Attributable to among Subjects, among Trials and between Days Variance.

		% VARIANCE			R
		SUBJECTS	TRIALS	DAYS	
TEST 1 (N=12)	KE ISOM	92.0	3.9	4.1	0.97
	KF ISOM	97.3	1.6	1.1	0.99
	PF ISOM	68.4	6.2	25.4	0.83
	EE ISOM	92.1	3.6	4.3	0.97
	EF ISOM	90.2	1.6	8.2	0.95
	HG ISOM	92.4	5.4	2.2	0.98
TEST 2 (N=13)	KE ISOM	94.0	2.8	4.3	0.98
	KE 36^{o}/sec	55.4	7.7	36.9	0.73
	KE 180^{o}/sec	80.7	9.1	10.2	0.88
	EF ISOM	88.3	3.9	7.8	0.94
	EF 36^{o}/sec	82.2	2.0	15.8	0.89
	EF 180^{o}/sec	82.3	7.3	10.4	0.90

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