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VITAL and HEALTH STATISTICS
DATA EVALUATION AND METHODS RESEARCH

Calibration of Two Bicycle Ergometers Used by the Health Examination Survey

A description of the calibration of two bicycle ergometers, including details on techniques and on precision of measurement, and the absolute workloads for each bicycle.

Washington, D. C. February 1967

U.S. DEPARTMENT OF
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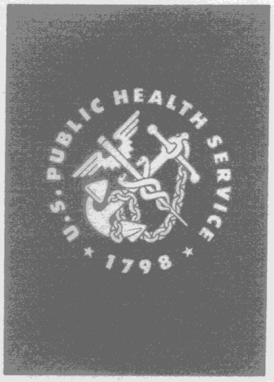

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FOREWORD

Between 1963 and 1965 the Health Examination Survey (HES) undertook a study of the noninstitutionalized population of the United States aged 6-11 years. A total of 7,119 children of a sample of 7,417 were examined. This group was so chosen as to represent a population of 23.8 million children.

One part of the examination was a test for exercise tolerance. The child was seated on a "bicycle," which he was instructed to pedal for 2 minutes. The "bicycle" was actually an ergometer. It was set at a predetermined load so that the rate of work that the child performed in pedaling was indicated by the dial setting. The child's pulse rate at the end of a 2-minute ride served to measure his response to exercise. Two different bicycle ergometers were used.

The question naturally arose as to the accuracy of the workload settings. This was a matter of concern for two reasons. If other populations were to be compared with the U.S. population using a similar test it was naturally important that the true work required by the HES test be accurately known. For example, a comparison of Swedish and American children which purported to show differences between these two populations in their "physical fitness" might understate or overstate the difference if the test instruments they used were calibrated differently. This was of less concern, however, in comparing different subgroups of U.S. children. For that purpose it was important to know how the two bicycle ergometers used by HES compared with each other, since it was entirely possible (if the bicycles were not calibrated at the same level) that apparent differences between subgroups of the population might really be differences between the bicycle ergometers used in their tests or that real population differences might be concealed.

The HES therefore contracted with Stein Industries, Inc., to conduct a physical calibration of the two ergometers used in the survey of children 6-11 years old. The results of this calibration are presented in this report. They are pertinent not only to the Health Examination Survey but also to other studies which use similar ergometers for population studies.

Tavia Gordon
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CONTENTS

IN THIS REPORT the calibration of two bicycle ergometers is described. These ergometers were used for measuring exercise tolerance in Cycle II of the Health Examination Survey, which consisted of examinations of a nationwide probability sample of the noninstitutionalized population of the United States aged 6-11 years.

The technique used in calibration is described, and the precision of measurement is indicated. At the prescribed pedaling speeds the true workloads were less than the indicated workloads. The amount of difference varied from one bicycle to the other. The bicycles differed in other performance characteristics as well. Both ergometers appeared to be stable during the period of testing; that is, while they were not in precise calibration they were apparently reliable.

SYMBOLS

Data not available	---
Category not applicable	. . .
Quantity zero	-
Quantity more than 0 but less than 0.05	0.0
Figure does not meet standards of reliability or precision	*

CALIBRATION OF

TWO BICYCLE ERGOMETERS USED BY THE HEALTH EXAMINATION SURVEY

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INTRODUCTION

This report describes the calibration of two ergometers—Model AM 368—manufactured by Elema-Schonander of Sweden. The work was performed by Stein Industries, Inc., of Kensington, Md.

The report explains the methods used, describes the special device constructed for the calibration, and tabulates the results. Also included are a brief summary of the results, a discussion of the sources of error, and the formulas to estimate the accuracy of the calibration technique.

The calibration described here was made for the purpose of determining differences in energy loading between two ergometers used in the Health Examination Survey (HES). The aim of the calibration was to obtain true measures of power, and consequently energy, expended by a subject as a function of the various load settings on the two machines.

It was found that in addition to a discrepancy between the two machines tested, each unit displayed inaccuracies in both pedaling speed (tachometer indications) and electrical workload selected by the operator.

PHYSICAL DESCRIPTION AND OPERATION OF ERGOMETER

The ergometer is a device for making controlled work and energy measurements based on the principle of presenting a constant powerload to the subject. This power expended over a known period of time can be converted to a known amount of work. Work is the integral of the power multiplied by the time during which that power is developed.

The ergometer consists of a bicycle seat and a pedal crank coupled to an electrical generator (see fig. 1). The output of the generator is controlled by an electrical servo system designed to keep the output voltage constant over a wide range of pedal shaft speeds. This voltage is impressed upon a series of load resistors which are, in turn, connected to the output circuit by individual switches. Thus, the operator may select the amount or size of the load applied against the subject.

Additional circuitry is incorporated in the ergometer to compensate for any drift in the load resistors due to temperature change inside the unit. The result is an essentially constant powerload during the testing period, provided

Figure 1. Illustration of the ergometer.

the pedal shaft speed is maintained within prescribed limits.

The subject supplies power to the ergometer by turning the pedals at nearly constant speeds, developing torque which results from the force exerted by his foot on the pedal. This torque can be measured by obtaining the product of the subject's force on the pedal times the distance from the center of the pedal to the center of the pedal shaft. The product of this torque (which is proportional to the force applied) and the number of revolutions per minute yield a figure representing the rate of work, or power.

Since the ergometer is so constructed as to yield a constant powerload over a fairly wide range of r.p.m., an unusual characteristic results in that as the speed of the shaft increases, the torque required to turn the pedal shaft decreases. Thus, as the subject tires and is unable to sustain a constant speed, the apparent drag increases as his pedal speed decreases. This differs, of course, from the sensation experienced on a real bicycle. There the torque is set by the drag associated with factors such as terrain and wind resistance, and it tends to remain constant. The sensation is that the amount of work increases with the speed. Thus, on a bicycle, by diminishing speed the rider decreases his rate of doing work and his rate of tiring. The ergometer, on the other hand, tends to tire the subject at a constant rate as he slows down by making the drag at the pedals increase.

CALIBRATION TECHNIQUES AND EQUIPMENT

A calibrating technique was required to ascertain whether the two ergometers did in fact present similar loads for similar switch settings. Besides measuring the uniformity between the two ergometers, it was necessary to be able to determine the actual force exerted by the subject upon the pedals when working against various loads.

A mechanical power source, consisting of a known rotational force, was applied to the sprocket shaft in such a way as to drive it at the nominal speed of 60 r.p.m., as well as 45 and 75 r.p.m. This simulated the subject's operation of the ergometer. The transmitted power for various settings of the load switches and for several different speeds was measured accurately.

The tests were performed on both ergometers within a few days of each other to avoid the possibility of drift or other changes taking place in the calibration apparatus between tests. The ergometers were in no way adjusted or altered prior to or during the calibration runs.

The calibrating accuracy was to be within 2 percent of true. In order to achieve such accuracy, it was necessary to keep the speed of the input shaft constant to within 1 percent while taking measurements on the ergometers.

A calibrating device was constructed consisting of an electric motor coupled to a Vickers hydraulic transmission (see Appendix II). The motor was rated at ½ horsepower and operated continuously at 1,725 r.p.m. The hydraulic pump transmission was constructed so that the speed of its output shaft could be carefully adjusted by moving an internal valve which regulated the length of the stroke of the pump piston.

The output of the transmission was connected to a speed reducer consisting of a sprocket gear and chain drive. The speed reducer was coupled to the output drive shaft which transmitted the torque through universal bearings to the pedal shaft of the ergometer being tested. Both pedal cranks were removed from the ergometer. This reduced the mass of the driven ergometer but had a negligible effect on the drag measurement.

The motor, transmission, and speed reducer made up the drive assembly, which was mounted on a rigid platform. The platform was suspended from the output drive shaft by a pair of pillow-block bearings. The drive shaft was supported from the floor by a second set of bearings. Thus the entire assembly was free to rotate about the drive shaft.

This configuration allowed an accurate measurement of the torque transmitted to the ergometer by simply balancing the moment created by the reaction of the load upon the suspended power source at any given shaft speed.

After an initial balancing at no-load, counter-weights were added to balance the drive assembly platform at the discrete loads chosen and at constant shaft speed.

The torque was then computed from the product of the counter-weights necessary to balance the drive assembly and the moment arm length (distance from the balance pan suspension point to the center of the drive shaft). The torque measurement thus derived was independent of the weight of the driving platform as well as all sources of drag within the drive assembly.

The drive shaft speed was carefully measured and constantly monitored by the method described in the section "Measurements and Procedures."

A final calibration of power delivered to the ergometer was made by averaging torque readings and multiplying by the angular frequency (speed in r.p.m.) of the drive shaft with appropriate conversion factors. These power figures then were tabulated against ergometer load switch settings.

MEASUREMENTS AND PROCEDURES

Each of the basic elements used in the calibration was initially checked against standards traceable to laboratory primary standards. The weights were checked on a scale balance to an accuracy better than ½ percent.

Primary tachometer measurements (see table 1) were made by counting revolutions of the pedal shaft with a stopwatch. The watch was checked with an electronic timer. After the ergometer tachometer was initially calibrated, a monitoring system was devised for keeping the angular frequency (shaft rotational speed) constant during the load calibration runs.

The speed monitor consisted of a "Proxi-Probe" inductive pickup and a Model 410 Carrier Amplifier System, both manufactured by Stein Industries, Inc., and a Hewlett-Packard Model

Table 1. Tachometer calibration: measured pedaling speed on specified ergometer units at indicated loads and pedaling speeds

Indicated load and indicated r.p.m.	Measured r.p.m.	
	#273	#271
200 kpm		
45	56.9	54.5
60	70.6	74.4
75	87.1	84.5
450 kpm		
45	56.1	59.4
60	70.4	71.9
75	86.9	87.7
750 kpm		
45	55.8	58.8
60	70.4	75.5
75	86.0	91.7
Average		
45	56.2	57.6
60	70.5	73.9
75	86.7	87.9

140A oscilloscope. The inductive probe was brought close to a projecting rod on the drive shaft (see Appendix II). The output of the probe was amplified by the carrier amplifier and displayed on the oscilloscope. The time base was set for 2 seconds sweep time and set for internal trigger.

Every third revolution triggered the oscilloscope, and the next succeeding pulse was displayed on the scope face with the sweep magnified 10:1. By making careful measurements of the point on the sweep where the second of the two pulses occurred, it was possible to obtain accurate and instantaneous speed readings.

The speed was continually monitored during all of the runs and readjusted as necessary.

The actual testing procedure began with the calibration of the weights to be used in balancing the drive assembly. Balancing of the assembly itself was accomplished next, after which the drive shaft was attached to the ergometer. The transmission was set to drive the ergometer at a given rate of speed. The shaft was timed for approximately 60 seconds to get the true r.p.m. indications.

At each load point (each setting of the switches) the pedal shaft speed was checked for about 10 seconds with the monitoring system, adjusted if necessary, and monitored again.

As the drive assembly became imbalanced because of the drag exerted against it from the electrical generator of the ergometer, weights were placed on the suspension balance pan at the end of the moment arm until the assembly regained and held balance for a period of 1 minute. The amount of weight required to balance the assembly was logged, the ergometer turned off, the load switches reset, and the drive assembly rebalanced without weights. This procedure was repeated for each of the load setting at intervals of approximately 3 minutes, with each test run requiring about 3 minutes.

The data collected (quantity of weights for each point in each run) were then multiplied by the length of the moment arm, yielding the applied torque. The torque, multiplied by the angular frequency (shaft speed) and appropriate conversion factors, yielded the calculated power in kpm/M (Kg-M/Min). (See Appendix I.)

RESULTS

Tables 1-3 show, respectively, the results of the tachometer calibrations, a summary of the ergometer load calibrations, and the detailed calibration data for each test run performed.

It should be noted that the tachometers on both units drifted considerably. Because of the

Table 2. Calibration averages: average load measurements on specified ergometer units at indicated loads and pedaling speeds

Indicated load	Calculated load		
	45/56 r.p.m.[1]	60/71 r.p.m.[1]	75/87 r.p.m.[1]
Unit #273			
200 kpm---------	168	182	230
250 kpm---------	212	228	271
300 kpm---------	260	279	321
350 kpm---------	306	329	375
400 kpm---------	354	377	418
450 kpm---------	404	427	485
500 kpm---------	449	471	535
550 kpm---------	497	522	582
600 kpm---------	546	577	642
650 kpm---------	597	627	697
700 kpm---------	644	676	749
750 kpm---------	691	723	799

Indicated load	Calculated load		
	45/58 r.p.m.[1]	60/74 r.p.m.[1]	75/88 r.p.m.[1]
Unit #271			
200 kpm---------	141	141	173
250 kpm---------	182	182	210
300 kpm---------	225	229	268
350 kpm---------	268	273	307
400 kpm---------	312	310	354
450 kpm---------	356	353	398
500 kpm---------	399	401	445
550 kpm---------	442	439	492
600 kpm---------	486	482	542
650 kpm---------	532	528	595
700 kpm---------	573	569	636
750 kpm---------	615	609	686

[1] Indicated r.p.m./true r.p.m.

Table 3. Calibration detail: load measurements on specified ergometer units at indicated loads and pedaling speeds

Indicated load	Calculated load								
	45/56 r.p.m.[1]				60/71 r.p.m.[1]				75/87 r.p.m.[1]
Unit #273									
200 kpm	174	168	162	166	176	180	181	191	230
250 kpm	212	216	208	213	222	226	226	236	271
300 kpm	258	263	257	261	272	278	277	287	321
350 kpm	306	307	305	307	323	329	327	337	375
400 kpm	357	353	354	353	370	378	376	384	418
450 kpm	408	405	402	402	421	425	425	435	485
500 kpm	454	449	447	446	464	472	468	481	535
550 kpm	502	495	494	498	515	524	519	531	582
600 kpm	542	546	546	548	568	583	573	583	642
650 kpm	605	595	593	596	618	632	624	633	697
700 kpm	647	642	643	644	667	680	674	683	749
750 kpm	688	692	691	691	719	722	719	732	799

Indicated load	Calculated load							
	45/58 r.p.m.[1]				60/74 r.p.m.[1]			75/88 r.p.m.[1]
Unit #271								
200 kpm	138	141	141	145	153	142	127	173
250 kpm	181	181	182	184	198	184	165	210
300 kpm	221	224	229	227	252	228	207	268
350 kpm	269	265	270	268	296	274	249	307
400 kpm	312	310	315	309	336	311	284	354
450 kpm	356	357	356	356	380	352	326	398
500 kpm	400	397	400	398	434	400	369	445
550 kpm	443	436	444	444	472	439	406	492
600 kpm	489	480	491	485	517	482	447	542
650 kpm	533	529	537	529	566	524	494	595
700 kpm	574	571	576	570	611	565	531	636
750 kpm	617	612	623	609	655	608	565	686

[1] Indicated r.p.m./true r.p.m.

wobble inherent in the needle indicator, it was difficult to determine indicated r.p.m. accurately. There appeared to be a 10 to 15 r.p.m. difference between indicated and true r.p.m. at all operating speeds, with a pronounced long-term downward drift noticeable in unit no. 273.

Further discussion of the data and their implication follows.

DISCUSSION OF RESULTS AND SOURCES OF ERROR

Error for all the calibrating procedures has been computed at less than 2 percent, as discussed below. Runs were repeated in part in order to spot check the results. An interval of several days between runs was allowed for spot checking. In each of the points so checked, the observable variance was under 1 percent.

An analysis of points of calibration on unit no. 271 shows that between the range of 45 and 60 r.p.m. (indicated), the ergometer presented a constant powerload for each switch setting independent of pedal shaft speed. Above 60 r.p.m. (indicated), however, the powerload increased. The difference ranged from approximately 20 percent at the low end to 10 percent at the high end of the observable range. In any case, all readings indicated that this unit was delivering less power than that selected by the switches. The deviation appeared to be about 20 percent from the true power output as measured at 60 r.p.m. (indicated) and at the true value of 500 kpm/M (Kg-M/Min).

Unit no. 273 exhibited a constant power difference between 45 and 60 r.p.m. (indicated): approximately 20 kpm/M (Kg-M/Min) measured throughout the entire range. At the higher shaft speeds, the difference was substantially greater—nearly 50 kpm/M (Kg-M/Min).

Deviation from true power output figures was substantially less than in unit no. 271; the values at 60 r.p.m. (indicated) were approximately 18 kpm/M (Kg-M/Min) below the values selected by the switch settings. This was within the 5 percent figure claimed by the manufacturer throughout most of the calibration range.

Short-term drift of the machines was so small as to be barely measurable. Over the first 10 minutes a drift of approximately 10 kpm/M (Kg-M/Min) was observed at most points. This time was long compared with testing intervals, and the long-term drift was not considered significant.

Several sources of error are inherent in the calibration technique chosen here. From the formula used in computing powerload (see Appendix I) these are rotational speed, counterweights, and moment arm.

The rotational speed was measured with an oscilloscope which was checked against a stopwatch. The watch was compared with an electronic timer and found to be accurate to within 10 seconds in 24 hours, or an error of ±0.011 percent. The error associated with timing the oscilloscope was estimated at 2 milliseconds in 1 second, or ±0.20 percent. Thus, the combined inaccuracies associated with reading and measuring the pedal shaft rotational speed produced an error of ±0.381 percent, or about 1/3 percent.

The counter-weights were checked at the University of Maryland. Weights of 100 grams and less were checked on an analytical balance with an accuracy to four decimal places. The larger weights were then compared with the smaller ones on a torsion balance. The maximum error was -0.53 percent, but the sum of all deviations was under -0.04 percent. All readings during the calibration procedure were corrected by adding to the logged amount a correction factor corresponding to the known deviations of the weights used.

The moment arm was measured with an accurate metal scale, but due to difficulties of measurement, accuracy was estimated at 1/8 inch in 24 inches, or ±0.50 percent.

In addition to these errors, an indeterminancy of measurement of the exact balance point due to the dynamic imbalance of the calibrating apparatus introduced another error factor This indeterminancy was estimated at 10 grams over most of the range, and at about 15 grams at the high end. This is equivalent to approximately 1 percent at the low end and 0.7 percent near the center of the range.

Therefore, summing all inaccuracies to determine worst case error, error factors of approximately 1.6 percent near the center of the

Table 4. Calibration error: standard error and relative error of load measurements on specified ergometer units at indicated loads and pedaling speeds

Indicated load	45/56 r.p.m.[1]	60/71 r.p.m.[1]	45/56 r.p.m.[1]	60/71 r.p.m.[1]
Unit #273	Standard error in kpm		Relative error in percent	
200 kpm----------------	5.0	6.4	3.0	3.5
250 kpm----------------	3.3	6.0	1.6	2.6
300 kpm----------------	2.8	6.2	1.1	2.2
350 kpm----------------	1.0	5.9	0.3	1.8
400 kpm----------------	1.9	5.8	0.5	1.5
450 kpm----------------	2.9	6.0	0.7	1.4
500 kpm----------------	3.6	7.3	0.8	1.5
550 kpm----------------	3.6	6.9	0.7	1.3
600 kpm----------------	2.5	7.5	0.5	1.3
650 kpm----------------	5.3	7.1	0.9	1.1
700 kpm----------------	2.2	7.1	0.3	1.0
750 kpm----------------	1.7	6.2	0.3	0.9
Indicated load	45/58 r.p.m.[1]	60/74 r.p.m.[1]	45/58 r.p.m.[1]	60/74 r.p.m.[1]
Unit #271	Standard error in kpm		Relative error in percent	
200 kpm----------------	2.9	13.0	2.0	9.3
250 kpm----------------	1.4	16.6	0.8	9.1
300 kpm----------------	3.5	22.5	1.6	9.8
350 kpm----------------	2.2	23.5	0.8	8.6
400 kpm----------------	2.6	26.0	0.8	8.4
450 kpm----------------	0.5	27.0	0.1	7.7
500 kpm----------------	1.5	32.5	0.4	8.1
550 kpm----------------	3.9	33.0	0.9	7.5
600 kpm----------------	4.9	35.0	1.0	7.3
650 kpm----------------	3.8	36.2	0.7	6.8
700 kpm----------------	2.8	40.1	0.5	7.1
750 kpm----------------	6.1	45.0	1.0	7.4

[1] Indicated r.p.m./ true r.p.m.

range and 2 percent at the low end are obtained. Another way to evaluate the relative error is to examine the data in table 3 by standard statistical methods. This is done in table 4. At each indicated load the standard error $\underline{s}$ ($\sqrt{\frac{1}{n-1}\,\Sigma(x_i - \bar{x})^2}$ in the usual notation) and the relative error (100 $s / \bar{x}$) are tabulated for each indicated load setting. The relative error is greater at lower loads and at higher r.p.m., but it is generally of the order of magnitude indicated by the previous calculations. Some of this "error," of course, represents variation in the ergometers' performance over the succession of runs, but it is evident from the previous reckoning that the ergometer variation must be small indeed and that almost all of the indicated variation represents measurement error.

The exceptions to this rule of high reliability are the measurements of bicycle no. 271 made at a nominal speed of 60 r.p.m. Relative error of the three runs at this speed ranged roughly between 7 and 10 percent. These high values may represent some technical lapse, but in all likelihood they are largely a measure of machine instability at that speed. The three runs were actually done at true speeds of 72, 77, and 84 r.p.m., respectively. The variation in speed arose from the great instability of the tachometer. In trying to reproduce a normal operating situation the machine was being used in a range outside of the recommended 45-75 r.p.m. and across a range of speeds. This may well be an accurate representation of the usual operating experience, but if it is, the operating experience with this machine includes a substantial measurement variability.

APPENDIX I

CALIBRATION FORMULAS

The powerload presented by the ergometer can be computed from the following formula:

$P_c : \Omega \times \tau$ or $P_c : 2\Pi f \times W \times d$

where

P_c = the calculated powerload

Ω = the angular frequency

τ = the torque transmitted into the ergometer

f = the rotational speed

W = the counter-weights

d = the moment arm

Since the readings on the ergometer load selector are in kpm/M (Kg-M/Min) the proper conversion factors were used. The weight measurements were directly in kilograms, and the moment arm was measured in inches. By converting to meters, the torque was computed in Kg-M. If the rotational speed is now ascertained in revolutions per minute and multiplied by 2Π, a multiplying factor is obtained. This factor times the torque yields the power in Kg-M/Min(kpm/M).

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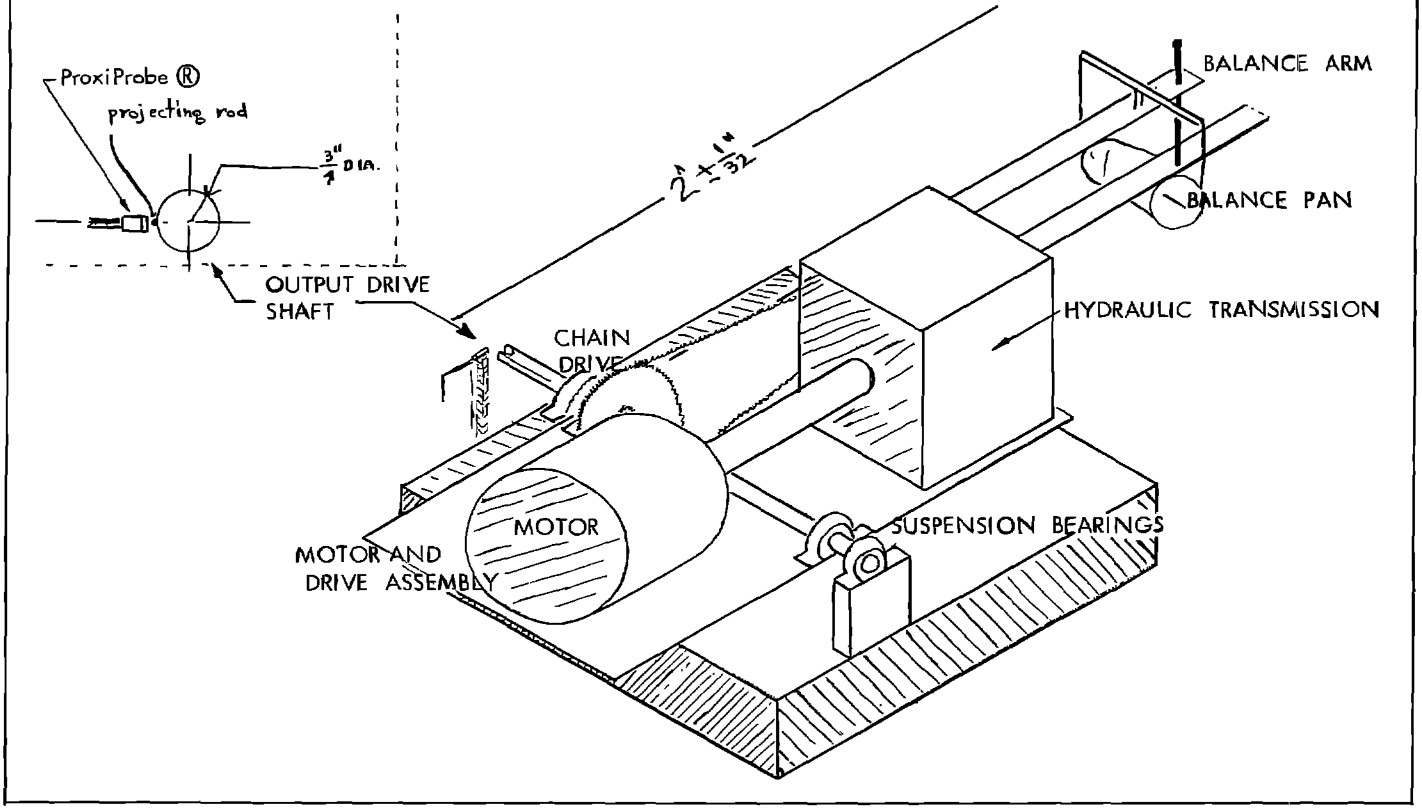
APPENDIX II

CALIBRATOR FOR ERGOMETER MODEL AM 368



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