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BICYCLE ERGOMETER INSTRUMENTATION TO DETERMINE MUSCLE AND BONE FORCES DURING EXERCISE

Final Report
NASA/ASEE Summer Faculty Fellowship Program--1994
Johnson Space Center

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Date Submitted:	July 28, 1994
Contract Number:	NGT-44-005-803

ABSTRACT

It is hypothesized that bone loss experienced by astronauts in zero gravity conditions may be curtailed by appropriate exercise. According to Wolf's law, bone regenerates when muscles produce stresses by pulling on the bone during daily activity and/or exercise on Earth. To use this theory to prevent or decrease bone loss, one needs to quantify musculoskeletal loads and relate them to bone density changes. In the context of the space program, it is desirable to determine musculoskeletal loads during exercise (using the bicycle ergometer in this case) so that one may make similar measurements on Earth and in space. In this manner, load measurements on Earth may be used as reference to generate similar loads during exercise in space. The work reported in this document entails a musculoskeletal load measurement system that, when complete, will provide forces at muscle insertion points and other contact points, on bone. This data will be used by Dr. Beth A. Todd, who is also a SFF working with Dr. Shackelford, as input to a finite element model of bone sections to determine stress distributions.

A bicycle ergometer has been instrumented to measure parameters needed to determine musculoskeletal forces during exercise. A primary feature of the system is its compactness. It uses small/light sensors without line-of-sight requirements. The system developed includes sensors, signal processing, a data acquisition system, and software to collect the data. The sensors used include optical encoders to measure position and orientation of the pedal (foot), accelerometers to determine kinematic parameters of the shank and thigh, load cells to measure pedal forces on the sagittal plane, and EMG probes to measure muscle activity. The signals are processed using anti-aliasing filters and amplifiers. The sensors' outputs are digitized using 30 channels of a board mounted inside a 486 class PC. A program sets the data acquisition parameters and collects data during a time period specified by the user. The data is put directly into a file on the hard disk in binary form. The 30 channels are sampled at 200 KHz, and each 30 channel scan is done at a rate of 1000 Hz. The instrumented ergometer has been flown in the KC-135 zero-gravity (zero-g) flight to collect information needed to determine musculoskeletal forces under these conditions. Similar information has been collected in 1-g conditions for comparison with the results from the zero-g case. At this time, the sets of data from both experiments are being processed. An existing methodology will be used to determine the kinematic parameters of the shank and thigh using accelerometer and encoder data. This methodology was developed during the fellow's previous NASA/ASEE fellowship and thanks to a Director's Grant. In the future, a methodology to determine the musculoskeletal forces using Newton's Law of Motion and optimization techniques will be developed to determine forces exerted by particular muscles.

INTRODUCTION

It has been determined that astronauts loose bone from the trabecular regions during space flight [1]. This loss is significant even when the permanence in zero-g conditions is as short as two weeks. Because of absence of gravitational forces, it is hypothesized that the reason for bone loss is the decrease of muscle pull activity on the bone during normal daily chores and during exercise. Therefore, one way to quantify bone remodeling activity is to determine the loading history on the bone. One may generate bone loading history during exercise on earth to determine the types of loads required for bone maintenance, and use this data as a template for musculoskeletal loads that must be generated in space. Therefore, musculoskeletal loads in space must also be determined. The instrumented ergometer system described in this report was developed with the objective of determining musculoskeletal forces during exercise on earth and in space.

The system developed uses a set of light and compact sensors that do not have line-of-sight requirements. The sensors measure motion parameters, loads, and electromyographic activity, which will be used to ultimately determine forces exerted by individual muscles. The methodology to determine the kinematics has already been developed. The methodology to determine musculoskeletal forces has been outlined, but has not yet been fully developed.

The sections that follow give a detailed description of each element of the system and its operation, and a description of the experiments performed including all the information needed to interpret the data collected. The task of turning the experimental data into musculoskeletal loads will be briefly outlined, and should be done in the near future.

SYSTEM CONFIGURATION AND OPERATION

A graphical representation of the instrumented ergometer system is shown in Figure 1. The load cells and encoders were connected directly to the data acquisition (DAQ) board. The EMG probes were passed through a recorder to amplify and filter to avoid aliasing. The recorder was used only because there was no other anti-aliasing filtering system available. The accelerometer signals were amplified using factory made low noise amplifier units (approximate gain of 100). A detailed description of each element of the system is provided in the experiment section.

The measurements provided by the above instrumented ergometer system will be used to determine forces exerted by individual muscles using the following two

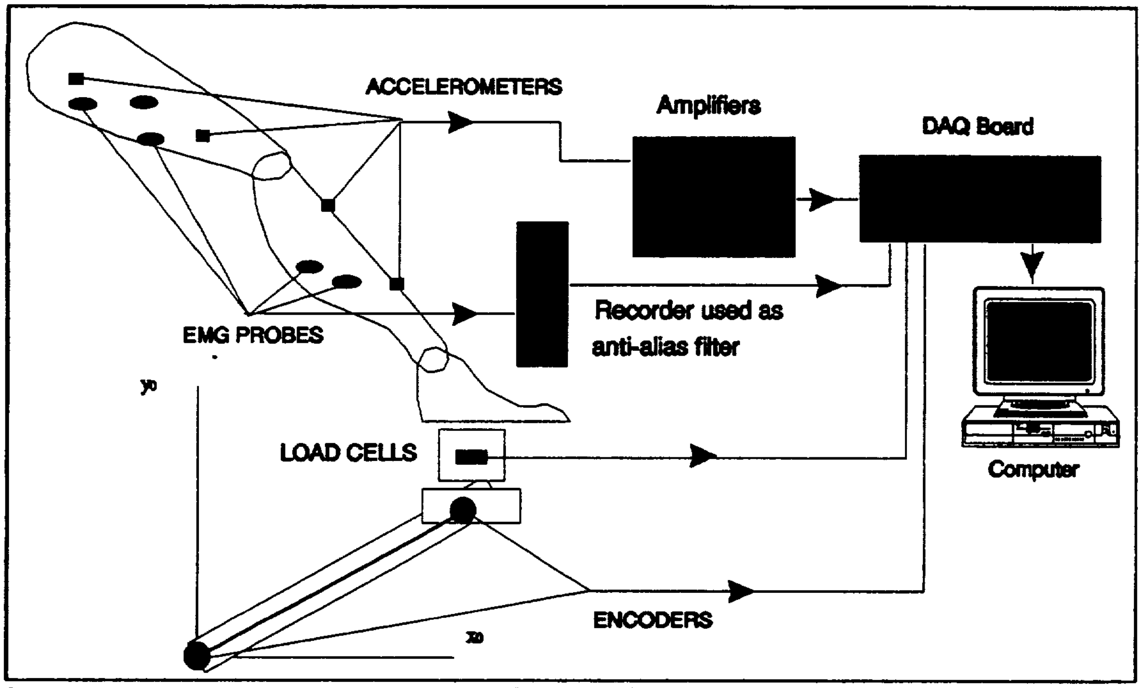

Figure 1.- Instrumented Ergometer System Configuration

step procedure: (1) Use Newton-Euler Equations of Motion of each body segment to determine a set of equations that relate the forces exerted by muscles on the segment bone and forces and torques applied by other bone neighboring sections at joints and contact points; this set of equations is indeterminate, meaning that there will be more unknowns than equations[2,3,4,5,6,7,8]. (2) Generate additional equations using optimization methods (optmize a criteria function)[9,2], heuristic knowledge about muscle activity during portion of a cycling exercise[7], muscle force sharing indicated by muscle, tendon, and moment arm[10], and other methods. Verification of the results will be done using the EMG measurements.

Part (1) of the procedure above requires the determination of the accelerations (angular and linear) of each body segment. A procedure to determine these accelerations using accelerations measured by the accelerometers and encoders has been developed and successfully simulated[11]. As mentioned earlier, the methods for the determination of forces is being developed using techniques in part (2) of the procedure outlined in the previous paragraph. The rest of the report describes the experiment and the data collected with two purposes: (1) to analyze qualitatively the values of loads, accelerations, and EMG activity during exercise, and (2) to prepare the data for use in the determination of musculoskeletal loads.

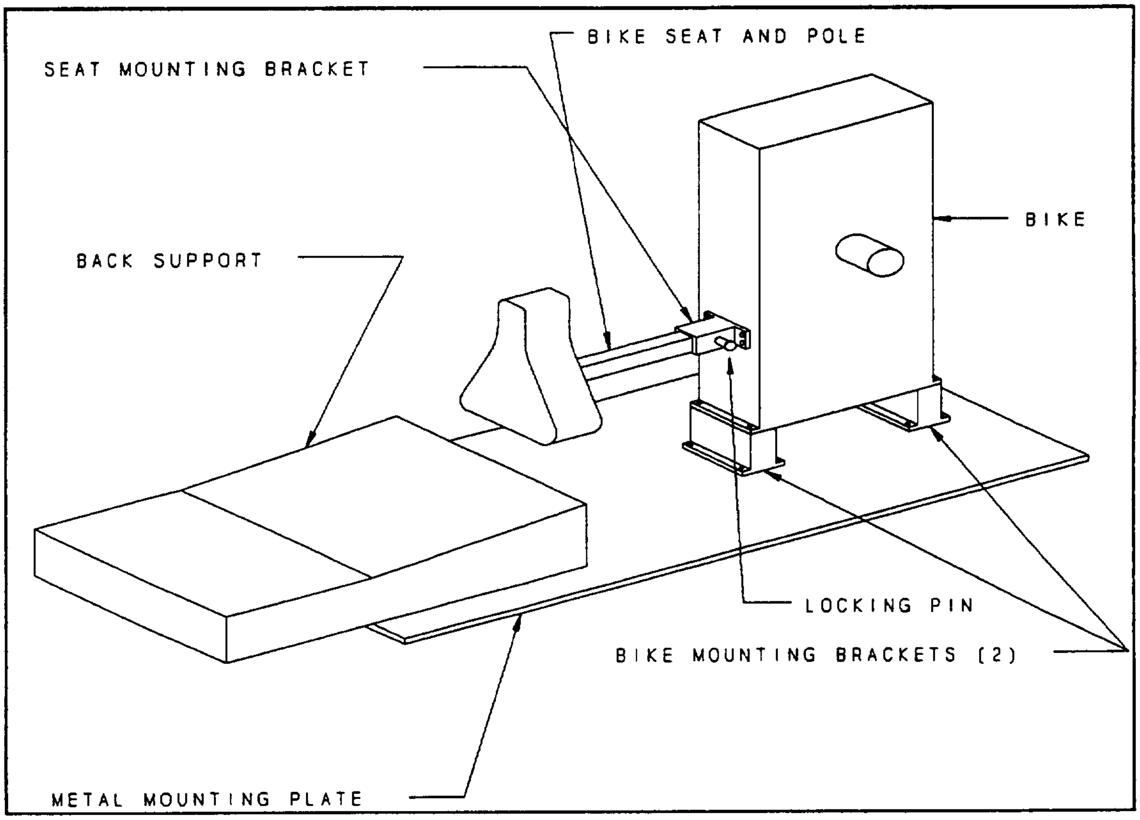

Figure 2.- Bicycle Ergometer mounting

EXPERIMENT

The experiment consisted in running the program after all sensors were mounted and connected. Each run corresponded to the duration of zero-g conditions during one parabolic flight path and lasted 20 or 25 seconds. Before the program was started, the pedal and crank initial positions were marked as a reference. Also, a file name and the experiment duration were input prior to each run. The ergometer assembly and mounting is shown in Figure 2. The overall experiment physical layout is shown in Figure 3. The data for each run was saved in the format shown in Figure 4. Figure 4 represents one scan of all 30 channels used. Data corresponding to the second scan starts in position 31 and ends in position 60. The rest of the data follows the same organization. Each position is filled by a two byte binary representation of an integer.

The experiment runs included various modes of exercise. Table 1 shows a list of the experiment data files and their descriptions.

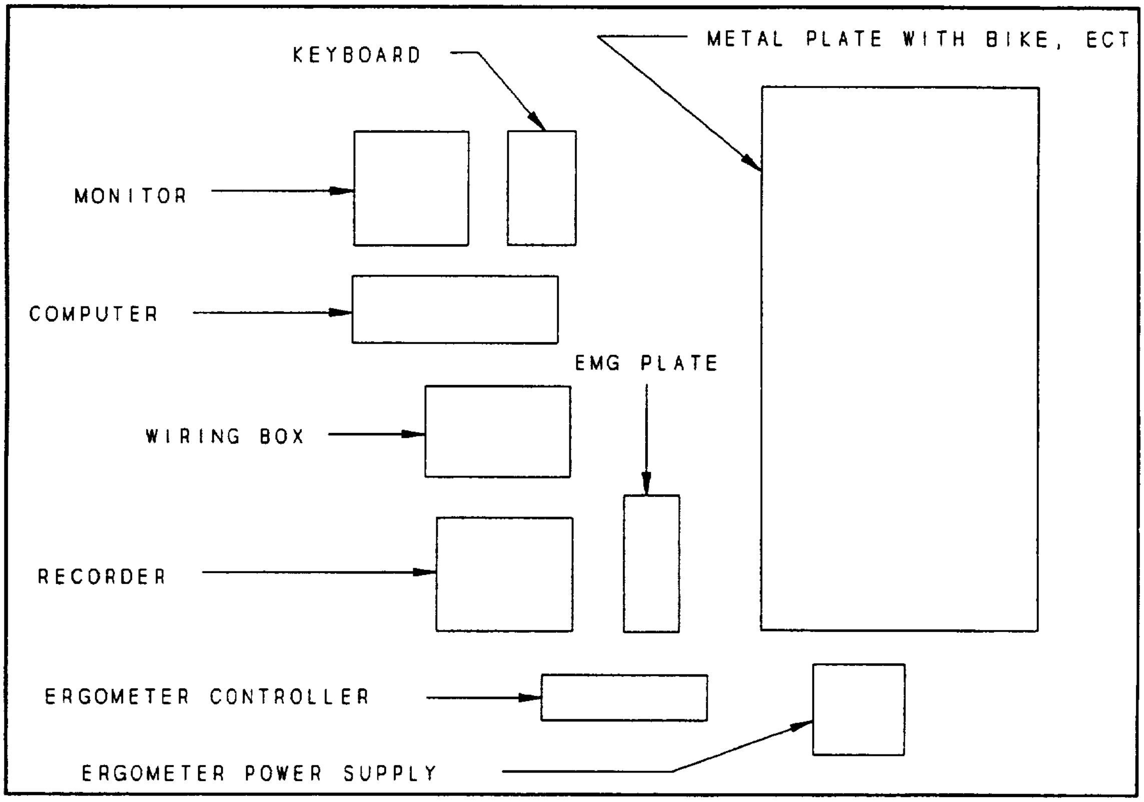

Figure 3.- System layout during the experiment

	ACCEL	EMG	ACCEL	L.C.	P. ENC.	C. ENC.
DIFFERENTIAL PAIR	8 . . . 15,		48 . . . 51,	52 . . . 55,		
CHANNEL #	0 . . . 7,	16 . . . 23,	24 . . . 27,	28 . . . 31,	32 . . . 34,	35 . . . 37
DAQ GAIN	1	1	1	10	1	1
	1 . . . 8,	9 . . . 16,	17 . . . 20,	21 . . . 24,	25 . . . 26,	27 . . . 30

POSITION FROM THE BEGINNING OF THE FILE FOR ONE SCAN

L.C. Load Cell
P. ENC. Pedal Encoder
C. ENC. Crank Encoder

Figure 4.- Organization of the Data File

Table 1.- EXPERIMENT DATA FILES

Filename	Description	Init. Pos.
p1.dat ... p7.dat g1.dat, g2.dat	Standard cycling (pedaling) Standard cycling on ground	47° from horiz.
r2.dat ... r10.dat	Resistive (squats)	43° from vert.
pu*.dat	pull ups	
ha*.dat	with shoulder harness	
s*.dat	squats with shoulder harness	
gpu*.dat,	Pull throughs on ground	
gpr*.dat	Presses on ground	
gtr*.dat	toe raises	
gs*.dat	shoulder harness	
gsc1.dat	shoulder harness standard cycling	

A complete description of each sensor system and their operating parameters are presented in the following sections.

Accelerometers

A total of 12 one dimensional accelerometers were used. These were bundled in groups of three to measure three orthogonal components of the acceleration at a point. Thus, three orthogonal components of acceleration were measured at four distinct points, two points on the shank and two points on the thigh (see Figure 1). Table 2 shows a detailed description of the accelerometers and their calibration. Each accelerometer was amplified by approximately 100 prior to digitization. The calibration includes the effects of this amplification. The gain shown is that of the data acquisition system. The nomenclature used to label the table columns translates as follows:

Ch = DAQ channel used
Scn = Position within the 30 channel scan

Gain = DAQ gain setting.

Table 2.- ACCELEROMETER PARAMETERS

ID	Ch.	Scn	Gain	Calibration (Volts)					
				→ 0g	↓ 1g	↑ -1g	↑ - →	→ - ↓	C -2g
SDX	02	3	1	0.36	0.73	.01	-0.35	-0.37	-0.72
SDY	25	18	1	0.23	0.62	-0.09	-0.32	-0.39	-0.71
SDZ	24	17	1	.17	.56	-0.27	-0.44	-0.39	-0.83
SUX	03	4	1	-0.23	.17	-0.69	-0.46	-0.40	-0.86
SUY	26	19	1	1.19	1.45	.83	-0.36	-0.26	-0.62
SUZ	07	8	1	.54	.88	.10	-0.44	-0.34	-0.78
TDX	04	5	1	-0.41	.09	-0.93	-0.52	-0.50	-1.02
TDY	27	20	1	-0.36	.04	-0.86	-0.50	-0.40	-0.90
TDZ	05	6	1	.28	.82	-0.31	-0.59	-0.54	-1.13
TUX	01	2	1	-0.29	.08	-0.71	-0.42	-0.37	-0.79
TUY	00	1	1	-1.05	-0.66	-1.40	-0.35	-0.39	-0.74
TUZ	06	7	1	-1.76	-1.40	-2.17	-0.41	-0.36	-0.77

Load Cells

Load cells measure forces on the sagittal plane on both pedals. Table 3 describes the parameters of these sensors. The x-right load cell was changed for the ground experiments and the table shows its sensitivity.

EMG Probes

These probes measure muscle activity on various muscles. Table 4 describes the parameters of these sensors.

Table 3.- LOAD CELL PARAMETERS

Ld. Cell	Ch.	Scn.	Gain	Sens.	Sign →	Sign ↑
x right	31	24	1	.800 mV/lb .9778 (gnd)	+ x-dir (pull foot to front)	
y right	29	22	1	.343 mV/lb		+ comp.
x left	30	23	1	.992 mV/lb	+ x-dir	
y left	28	21	1	.28 mV/lb		- comp

Encoders

Encoders measure the crank position and the right pedal position. The parameters of the encoders are shown in Table 5.

SOFTWARE

The software for data acquisition was developed using LabWindows/CVI from National Instruments, Inc., Austin, TX. The software and data acquisition board reside in a 50 MHz-486 IBM compatible PC with 16MB of RAM. The data acquisition board used is the AT-MIO-64F-5 board with 64 single ended analog inputs. The program writes the digitized data directly to disk and is run from the LabWindows/CVI environment. Inputs to the program include an ASCII text channel-gain file called "gain30.dat" that resides in the CVI directory, the name of the file for the data, and the scanning frequency, which are input by the user. The scanning frequency used was 1000 Hz.

DATA COLLECTION

Data was collected during the KC-135 zero-g flight and later on ground. During the flight, a data file was created almost for each 20 or 25 seconds of zero gravity time during the parabolic flight paths. The organization of each data file is detailed in Figure 4, and descriptions of each data file are shown in Table 1.

Table 4.- EMG PROBE PARAMETERS

Probe	Ch.	Scn.	Gain	Performance at ±6V		
				60Hz	500Hz	1000Hz
1 peroneous longus	16	9	10	352	357	358
2 lateral gastrocnemius	17	10	10	349	355	356
3 medial gastrocnemius	18	11	10	341	346	347
4 soleus	19	12	10	347	352	353
5 flexor hallux	20	13	10	365	371	372
6 peroneous brevis	21	14	10	358	364	365
7 extensor digitorum	22	15	10	347	353	354
8 tibialis anterior	23	16	10	363	368	369

DATA PROCESSING

Reduction of the data collected during the experiment has not yet been done. Dr. Shackelford's group, including myself, is currently in the process of extracting relevant information from the experiment's data files.

PENDING TASKS

The pending tasks to determine musculoskeletal forces include:

1. Interpret pedal and crank encoder information.
2. Using the positions of the accelerometers extracted from x-ray images of the subject's leg, define accelerations in the sagittal plane at each accelerometer mounting location on the shank and thigh. Extract acceleration components on the sagittal plane.
3. Use accelerations at the accelerometer locations and the geometry associated with the body section to determine angular velocity and acceleration of the section, and the acceleration of the center of mass.
4. Use the Newton-Euler equations of motion and other optimization and heuristic equations to determine forces exerted by particular muscles.

Table 5.- ENCODER PARAMETERS

Encoder	Ch.	Scn.
Ped. A	32	25
Ped. B	33	26
Ped. X	34	27
Crnk. A	35	28
Crnk B	36	29
Crnk X	37	30

5. Provide musculoskeletal forces and points of application for input to a finite element analysis of the section bone.

CONCLUSIONS AND RECOMMENDATIONS

A bicycle ergometer has been instrumented to measure parameters needed to determine musculoskeletal forces during exercise. This system, which includes hardware and methodologies, was conceived as a tool to help determine the causes for bone loss by astronauts that remain in zero-g conditions during space missions, and also as a tool to synthetase countermeasure exercises to decrease bone loss. The first prototype system was built and tested in zero-g conditions and on ground. The measurement system appears to have operated satisfactorily, and the data is being readied for use with methodologies to determine forces exerted by muscles and bone. These forces will be used as input to a finite element analysis model currently being developed by Dr. Beth A Todd[12] who also works with NASA Colleague Dr. Shackelford.

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APPENDIX

Parts List

The sensors and instrumentation used in the system are listed below. This list is provided so that the reader may access detailed information about these parts by reviewing the manufacturers' literature.

Name	Spec.	Description	Manufacturer
Crank Encoder	ERO-1324	512 lines/rev. optical encoder	Heidenhain, Traunreut, Germany.
Pedal Encoder	M20051221031	512 lines/rev. optical encoder	Dynapar Corp., Gurnee, IL
Accelerometers	EGAXT-10	±10g range strain gauge acc.	Entran Devices, Inc., Fairfield, NJ
Pedal Load Cell (shear)	ELF-TC1000-250	250 lbs range load cell	Entran Devices, Inc., Fairfield, NJ
Pedal Load Cell	ELH-TC590-500	500 lbs range load cell	Entran Devices, Inc., Fairfield, NJ