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Introduction

As a biological tissue, muscle adapts to the demands of usage. One traditional way of assessing the extent of this adaptation has been to examine the effects of an altered-activity protocol on the physiological properties of muscles. However, in order to accurately interpret the changes associated with an activity pattern, it is necessary to employ an appropriate control model. There exists a substantial literature which reports altered-use effects by comparing experimental observations with those from animals raised in small laboratory cages (e.g., Steffen and Musacchia, 1984; Templeton, Padalino, Manton, Glasberg, Silver, Silver, DeMartino, Le Coney, Klug, Hagler, and Sutko, 1984). Some evidence suggests that small-cage-reared animals actually represent a model of reduced use. For example, laboratory animals subjected to limited physical activity have shown resistance to insulin-induced glucose uptake which can be altered by exercise training (Mondon, Dolkas, and Reaven, 1983).

This project concerned the basic mechanisms underlying muscle atrophy. Specifically, the project addressed the issue of the appropriateness of rats raised in conventional-sized cages as experimental models to examine this phenomenon. The project hypothesis was that rats raised in small cages are inappropriate models for the study of muscle atrophy. The experimental protocol involved: (1) raising two populations of rats, one group in conventional (small)-sized cages and the other group in a much larger (133x) cage, from weanling age (21 days) through to young adulthood (125 days); (2) comparison of size- and force-related characteristics of selected test muscles in an acute terminal paradigm.
Methods

Housing

Male and female Sprague-Dawley rats were raised from weanling age (21 days) for 89-156 days ($\bar{X} \pm = 141 \pm 17$) in either of two sized cages. The small-cage animals were raised in conventional small laboratory cages (20 cm x 47 cm x 25 cm, 3-5/cage). The large cage provided approximately 133x more usable surface area (floor and 4 cage walls) for the animals and included climbing structures and exercise wheels. The activity of neither group of animals was monitored. The rats were provided with food and water ad libitum.

Two batches of animals were studied. In the first group (Batch 1), the males were raised and studied first; the females were procured subsequently. In the second group (Batch 2), the males and females were obtained at the same time and raised concurrently although in separate cages. By chance, but of subsequent relevance, the two batches were raised in two different buildings. All other details of the experiments were identical for the two groups.

Preparation

Terminal experiments were performed with the rats under halothane anesthesia. The anesthesia was delivered via a face mask, initially at a concentration of 4% and flow rate of 5 L/min. Following intubation of the trachea, anesthesia was maintained at a pain-free level for the extent of the experiment at halothane concentration of 1-2% as needed in a 50% N₂O-50% O₂ mixture with a total flow of 0.6 L/min. Respiration rate (90-120 breaths/min), percent expired CO₂, and rectal temperature (35-37°C) were monitored and adjusted to maintain homeostasis throughout the experiment. The left soleus and extensor digitorum longus muscles were surgically isolated by removing overlying and adjacent musculature. All branches of the sciatic nerve were transected near the hip, and those branches innervating soleus (soleus muscle nerve) and extensor digitorum longus (lateral peroneal nerve) were isolated for subsequent stimulation.
The animal was secured in a rigid frame, and the left hindlimb was clamped with the knee at an angle of about 120 degrees. The test muscles were maintained in vivo in a paraffin oil-filled bath at a temperature of 36 ± 1°C.

**Recording Procedures**

The test muscles were activated with a monopolar, stainless-steel, hooked wire electrode (referred to a similar electrode in an adjacent denervated muscle) by supramaximal cathodal stimulation (3-5x threshold, 0.1 ms square waves) of their nerves. The force elicited by such activation was measured by a force transducer that was attached to the tendon of the muscle by a low-compliance ( <0.03 μm/N/cm) dacron line (X ± SD length = 15.6 ± 1.3 cm). The whole-muscle electromyogram (e.m.g.) was measured with a spring-mounted, flexible, stainless-steel, intramuscular electrode (18 mm long, 120 μm thick, 40 μm tip) that was thrust into the distal one-third of the muscle, perpendicular to the long axis of the muscle. The intramuscular electrode was referred to a similar electrode placed in an adjacent denervated muscle.

Preliminary experiments indicated that the optimum muscle length for peak twitch force, for both soleus and extensor digitorum longus, was achieved when the muscle was stretched to exert a passive force of 0.15 N. Throughout the test, the length of the test muscle was altered to sustain a passive force of 0.15 N. No attempt was made to determine length-tension relationships during the present experiments for fear of fatiguing the muscle.

**Experimental Protocol**

Each muscle was activated separately with the following 5-step protocol: (1) 32 twitches at 0.5 Hz were elicited by stimulation of the nerve to both evaluate and circumscribe the effects of treppe; (2) a single tetanus of 100 Hz for 500 ms to determine tetanic force (this stimulation elicited approximate peak force in soleus, but stimulation rates of 250 Hz are required to elicit peak force in extensor digitorum longus (Close, 1964); (3) a 6-min application of a standardized stimulus regimen (Burke, Levine, Tsairis,
and Zajac, 1973) which involved repetitive intermittent stimulation (40 Hz) of the nerve with trains of 13 stimuli, each train lasting 330 ms and occurring once each second to evaluate fatigability; (4) 8 twitches at 0.5 Hz to evaluate the effects of the fatigue test on twitch force; and (5) two 100 Hz tetani, 10 s apart to evaluate the effects of the fatigue test on tetanic force. Approximately five seconds elapsed between consecutive phases of the protocol. The stimulus protocol was controlled with a small laboratory computer. Data were recorded on-line with the computer and on FM magnetic tape for a more detailed off-line analysis.

The animal was then terminated with an intracardiac injection of magnesium sulfate. The two test muscles were removed, frozen in isopentane cooled to its melting point, and stored at -70°C for subsequent histochemical analysis.

Data Analysis

Age and body weight were recorded for each rat at the time of the physiological experiment.

Physiological. The issues addressed in the first full-length paper (see Results) concern the affects of cage-size and gender on the force production capacity of the two test muscles as revealed by the above stimulation protocol. Each twitch was characterized by determining the peak force (N), time-to-peak force (ms), and half-relaxation time (ms). The peak force (N) was determined for each of the three 100 Hz tetani. For the 360 trains of the fatigue test, peak force, time-to-peak force, and two relaxation times (i.e., time for decay of force from 90% to 50% and from 50% to 20%) were determined. The Fatigue Index was defined as the peak force of the 360th train of the fatigue test expressed as a percent of the peak force of the initial train.

The e.m.g., which comprised the action potentials associated with each train of stimuli, was represented by the averaged waveform, and quantification was based on this average waveform. Measurements on the average waveform included four measures of amplitude, four of duration, and area, each of which reveals different features of muscle
action-potential generation, and propagation. The e.m.g. measurements are defined in the following manner: (1) absolute peak-to-peak amplitude, the magnitude of the difference (mV) between the absolute maximum and minimum; (2) first peak-to-peak amplitude, and magnitude of the difference (mV) between the maximum of the initial positive phase and the minimum of the subsequent negative phase; (3) mean amplitude, the ratio (mV) of area to waveform duration; (4) "mean" amplitude, the ratio (mV) of area to peak-to-peak duration; (5) baseline-to-baseline duration, the time (ms) from the beginning to the end of the waveform where the beginning and end are defined as a 5% deviation of the waveform from the preceding and succeeding baselines; (6) peak-to-peak duration, the time (ms) between the maximum of the initial positive phase and the minimum of the subsequent negative phase; (7) peak-to-peak rate, the average rate (mV/ms) of change between the initial positive-phase maximum and the negative-phase minimum; (8) normalized peak-to-peak rate, the reciprocal (1/ms) of peak-to-peak duration; (9) area, the integral (mV·ms) of the e.m.g. waveform where the beginning and end are defined for the measurement of baseline-to-baseline duration.

Histochemical. Serial frozen sections (10 μm in thickness) from the middle one-third of the muscle belly were cut, with alternate sections stained for succinate dehydrogenase (SDH) according to a modification of the methods of Pette and colleagues (Pette, Wasmund, and Wimmer, 1981; Pette, 1981) or myosin ATPase (pH 9.3 and 4.3) according to the methods of Guth and Samaha (1972). The fiber-type composition of the muscles was determined by classifying approximately 300 fibers per muscle (range = 265-368) located in the more central region of the cross section. Fibers were classified according to the nomenclature of Peter, Barnard, Edgerton, Gillespie, and Stempel (1972): SO (slow, oxidative) fibers stained light for myosin ATPase (using the alkaline preincubation) and intermediate to dark for SDH; FOG (fast-contracting, oxidative, and glycolytic) fibers stained dark for both ATPase and SDH; and FG (fast-contracting, glycolytic) fibers stained dark for ATPase but light for SDH. The relative percent
contribution of each fiber type was determined by dividing the number of fibers of a given type by the total number of fibers counted in that muscle and then multiplying by 100. These values represent the average of results from two independent observers. In addition, a subset of these fibers (70-100 fibers/muscle) were characterized in more detail through the use of a computer-assisted image processing system (made available by Dr. V.R. Edgerton, Department of Kinesiology, UCLA). This involved a microphotometric analysis of SDH activity according to the methods of Castleman, Chui, Martin, and Edgerton (1984) and determination of cross-sectional area.

To test for significant effects due to cage-size, gender, or batch, a multiple analysis of variance was used. A Newmann-Keuls comparison was used for post-hoc analysis with the critical value for significance of $p < 0.05$. Statistical differences in fatigability were assessed with single and multiple linear regression analyses and with an analysis of variances.
Results

The experimental results accumulated during this three-year project have been reported to the scientific community in two formats: (1) as ten abstracts presented at meetings of national and international societies; and (2) as five full-length papers. For this report, the abstract citations are listed, and the abstracts are attached at the end of the report; and summary outlines of the full-length papers are provided. Complete manuscripts can be provided if it is deemed desirable.

Abstracts


Papers

The results and conclusions of the project are described fully in the following five papers. Drafts of these manuscripts are available upon request.

1. "Effects of cage size and gender on the properties of developing rat hindlimb muscle."

   a. Male and female Sprague-Dawley rats were raised in separate groups from weanling age in either of two cage sizes. In terminal experiments, cage-size and gender effects were assessed with measures of size, force, contractile speed, fatigability, muscle fiber-type composition, and oxidative-enzyme activity for two test muscles, soleus and extensor digitorum longus.

   b. In general, cage size did not affect any of these measures.

   c. Similarly, apart from well-documented gender differences (e.g., muscle : body mass, twitch : tetanus force) the effect of cage size was similar for both male and female rats. There was, however, a greater variability (coefficient of variation) in many of the test measures exhibited by the female rats.
d. One group of large-cage male animals did demonstrate a significant effect of cage size relative to control animals. However, this observation probably reflected an environment effect due to the physical characteristics of the environment in which that particular cage was located.

e. It appears that rats of either gender raised in conventional laboratory cages represent an appropriate experimental model for altered-use paradigms.

2. "Fatigability of rat hindlimb muscle: E.m.g.-force relationship."

a. An experimental protocol designed to assess fatigability in motor units (Burke, Levine, Tsairis, and Zajac, 1973) has been applied to the whole-muscles of anesthetized adult rats and the electromyogram (e.m.g.)-force relationship monitored over the course of the test.

b. The animals were raised in either a small or a large cage. As a result, both test muscles (soleus and extensor digitorum longus) exhibited a wide range of fatigability, which was defined as the decline in isometric peak force at 6 min, such that the data for each test muscle were separated into groups of high, intermediate, and low fatigability.

c. The e.m.g. was quantified with four measures of amplitude, four duration variables, and one interaction term (area). Correlation analyses indicated that the e.m.g. was adequately represented by one measure of amplitude (absolute amplitude), one of duration (peak-to-peak duration), and area.

d. The e.m.g.-force relationships for soleus varied markedly between the three fatigability groups. In contrast, all three extensor digitorum longus groups displayed qualitatively similar e.m.g.-force relationships over the course of the test.

e. Multiple regression analyses indicated that the e.m.g. parameters were able to predict peak force better for extensor digitorum longus than for soleus.
Furthermore, for both test muscles the prediction was best for the high fatigability group.

f. The associations between e.m.g. and force appeared to depend upon the measure used to quantify the e.m.g., the fiber-type composition of the test muscle, and the degree of fatigability exhibited by the muscle.

3. "Fatigability of rat hindlimb muscle: Coexistence of potentiation and force decline."
   a. An experimental protocol designed to assess fatigability in motor units (Burke, Levine, Tsairis, and Zajac, 1973) has been applied to whole muscle of anesthetized adult rats in order to study the effects of the test on the magnitude of twitch potentiation.
   b. The animals were raised in either a small or large cage. As a result, both test muscles (soleus and extensor digitorum longus) exhibited a wide range of fatigability, defined as the decline in isometric force observed at 6 min, and twitch potentiation, defined as the increase in twitch force observed after, compared to before, the fatigue test.
   c. In the soleus, 57% (42/74) of the muscles exhibited fatigue (i.e., force at 6 min less than 100% of initial force); of these, 14% (6/42) also exhibited potentiated postfatigue-test twitch force. In contrast, all (68/68) extensor digitorum longus muscles exhibited fatigue, and of these, 46% (31/68) also showed twitch potentiation.
   d. In both test muscles, an inverse linear relationship was found between the degree of twitch potentiation and the magnitude of fatigue exhibited, although the relationship in soleus was different from that in extensor digitorum longus.
   e. Some recovery of the whole-muscle e.m.g. was evident between the end of the fatigue test and the first posttest twitch. However, there was no correlation between the degree of twitch force potentiation and any of the e.m.g. parameters studied.
f. The simultaneous occurrence of whole-muscle fatigue and twitch potentiation in some muscles suggests that the mechanisms underlying these two phenomena affect different sites within the muscle, but the linear relationship suggests that they are not totally independent of one another.

4. "A comparison of qualitative and quantitative histochemical classification of muscle fiber types."
   a. The metabolic heterogeneity seen within a given muscle fiber type, first described for fibers classified on the basis of myosin ATPase staining, has been confirmed for fibers classified according to the SO-FOG-FG scheme of Peter, Barnard, Edgerton, Gillespie, and Stempel (1972). All 3 fiber types exhibited a broad range of succinate dehydrogenase activities as determined by quantitative histochemical techniques.
   b. In soleus, mean SDH activity for FOG fibers was significantly greater than that for SO fibers; whereas in extensor digitorum longus, mean values for SO and FOG fibers were identical to each other but significantly greater than that for FG fibers.
   c. There was considerable overlap of SDH activities for the 3 fiber types precluding differentiation of fiber type based strictly upon oxidative potential. This, combined with the similarity of values for soleus SO fibers and extensor digitorum longus FG fibers, suggests that the differences in fatigability which characterize these 3 fiber types are not due solely to the differences in their oxidative capacity.

5. "The effects of disuse on skeletal muscle."

This final manuscript is a review which is organized in the following manner:

Effects of Reductions in Muscle Usage

  Models of Reduced Use

-12-
Neural Alterations
Muscular Alterations

Effects on Muscle Properties

Morphological Changes
  Macroscopic
  Ultrastructural

Histochemical and Biochemical Changes
  Metabolic Capacity
  Myofibrillar Components
  Additional Biochemical Alterations

Fiber-Type-Distribution

Physiological Changes
  Membrane Properties
  Contraction Time
  Force
  Fatigability

Effects on Motoneuron Properties

Potential Relevance of Overuse Models

Effects of Environment
  Central Nervous System
  Muscle
References


ABSTRACT

In preliminary experiments, we found that medial gastrocnemius (MG) motor units in cage-reared rats were unusually sensitive to fatigue, a test for which is required to distinguish between FF- and FR-unit types. This observation prompted an analysis of whole-muscle fatigue. It revealed an impairment of the electrochemical process of neuronal excitation-contraction coupling at one or several sites between motor axons and the contractile machinery. (Supported by NASA Grant NAGW-338).

INTRODUCTION

Following preliminary experiments (see Abstract), we undertook an analysis of whole-muscle fatigue in the MG of cage-reared rats, together with an estimation of the fatigability characteristics of MG in a theoretical "noncaged-reared" rat model, assuming the theoretical muscle would have unit properties like those found in hindlimb muscles of noncage-reared cats (3,5,6).

METHODS

We used 500 g male and female 100-day old Sprague-Dawley rats, who had spent their life in 46-49 x 25-28 x 20 cm cages (4-7/cage). Such confinement is typical for commercially bought rats. Under pentobarbital sodium anesthesia (30-70 mg/Kg, I.P.), MG was prepared for force and EMG measurements (3,5,6).

RESULTS

Experiments. Fig. 1 shows force and EMG responses of MG (N = 7). Note three points:

1. Before the fatigue test, the disparity between force output for direct and nerve stimulation was greater than considered normal (2,4).

2. The fatigue test produced more substantial reductions in force and EMG than anticipated (3,5). Unfortunately, there are no data comparable to Fig. 1 for noncage-reared rats. However, Table 1 (lines 8, 11) suggests that EMG (force) reduction would be 23% (62%) in the theoretical MG as compared to 66% (79%) in our test MG (Fig. 1).

3. Intermittent and abrupt changes in EMG amplitude were a feature of each stimulus train of the fatigue test, even before force declined.

Estimations. Three assumptions in the Table 1 estimations require explanation:

1. Values for the relative distribution of the different fiber types (Table 1, line 1) are only available for cage-reared rats. They should not differ markedly in noncage-reared rats (3).

2. The assumption that the amplitude of the EMG co-varies with muscle-fiber diameters 3/2 is based on measurements made on "in-continuity" mammalian nerve axons (8).

3. At first glance, the assumption might seem far-fetched that relative (inter-unit) features of motor-unit anatomy (Table 1, lines 1-4), force development (line 5) and fatigueability (lines 7, 10) are similar for rat MG and cat tibialis posterior (TP; footnotes 3-4). However, the specific tension (force/cross-section) of muscle tissue is quite similar across species (6), as are presumably the EMG:force relationships.

DISCUSSION

Orderly motor-unit recruitment (3) should prevail in cage-reared rats with cumulative activation (recruitment) of progressively more forceful units for progressively stronger contractions. As a result, it is likely that the FF units of cage-reared rats are used to less extent than the less forceful FR and S units (3, 6). On this basis, we propose that the impairment in neuronal excitation-contraction coupling observed in these experiments is more pronounced in FF than FR and S units. We also anticipate that the observed impairments would be less in the soleus (SOL) muscle because, for the motor activities possible in a confined environment, SOL is presumably used to a greater extent than MG (3,6). Conversely, the observed deficits should be similar in another commonly studied muscle, extensor digitorum longus (EDL), because, like MG, its usage is limited during less demanding contractions (unpublished observations).

To address these issues, we intend to examine the dependence of the observed impairments on the fatigability of muscle by comparing the fatigue profiles of MG, SOL and EDL in exercise-deprived, exercised-exposed and wild rats. The existence of such a relationship would underscore the desirability of assuring an appropriate level of functional integrity of test muscles prior to the application of a disuse protocol to simulate weightlessness.
Fig. 1. Reduction in EMG and force output of the whole MG muscle of a cage-reared rat. Upper force profiles: averages of 8 supramaximal twitches (1 Hz). Lower force and EMG traces: single-sweep records of subfused tetani (40 Hz). Stimulus duration; 2 ms for direct intramuscular stimulation (A, A1), 0.1 ms for muscle nerve (B, B1). Arrows (mins): stimulus sequence (interstimulus intervals). Fatigue tests: 330 ms-duration 40 Hz stimulus trains at 1 Hz for two min. Records indicate 1st (B), 31st, 61st and 121st (B1) trains. Amplitudes of EMG (mean) and force (peak) expressed as reduction from "control" values (OZ). Insert: sites at which fatigue might occur during muscle-nerve stimulation (7).

TABLE 1. Estimation of Mean Reductions in EMG and Force Output of MG Motor Units of Theoretical "Noncage-reared" Rats During a Fatigue Test

<table>
<thead>
<tr>
<th>Unit (Fiber) Type</th>
<th>PF(FO)</th>
<th>FR(FOG)</th>
<th>SO(SO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Muscle fiber distribution (%)</td>
<td>38</td>
<td>58</td>
<td>4</td>
</tr>
<tr>
<td>(2) Relative muscle-fiber diameter</td>
<td>1.26</td>
<td>0.95</td>
<td>0.79</td>
</tr>
<tr>
<td>(3) Motor-unit innervation ratio</td>
<td>1.26</td>
<td>0.84</td>
<td>0.90</td>
</tr>
<tr>
<td>(4) Motor-unit distribution (%)</td>
<td>29</td>
<td>67</td>
<td>4</td>
</tr>
<tr>
<td>(5) Relative force ratio</td>
<td>2.20</td>
<td>0.61</td>
<td>0.19</td>
</tr>
<tr>
<td>(6) Contribution to whole-muscle EMG (%)</td>
<td>49</td>
<td>49</td>
<td>2</td>
</tr>
<tr>
<td>(7) EMG reduction after 2 min fatigue test (%)</td>
<td>40</td>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>(8) Contribution to whole-muscle force (%)</td>
<td>20</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>(9) Force reduction after 2 min fatigue test (%)</td>
<td>60</td>
<td>39</td>
<td>1</td>
</tr>
<tr>
<td>(10) Force reduction in whole-muscle force (%)</td>
<td>96</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>(11) Contribution to reductions in whole-muscle force (%)</td>
<td>58</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

1 Test described in Fig. 1.
2 Cage-reared rat MG data (1).
3 Noncage-reared cat TP data (4,5).
4 Based on fused (100-200 Hz) tetanus value.
5 Mean number of muscle fibers in motor unit.
6 Amplitude of extracellularly recorded EMG assumed to co-vary with fiber diameter 3/2 (7).
7 Reduction in mean value(s) for 121st stimulus train with respect to 1st train.

REFERENCES
NEURAL FACTORS IN WHOLE-MUSCLE FATIGUE OF RAT SOLEUS AND MEDIAL GASTROCNEMIUS MUSCLES. MJ Joyner,* RM Enoka,* LL Rankin,* KA Volz,* and DG Stuart* (intr. by D Van Wyck), Departments of Physiology and Physical Education, University of Arizona, Tucson, Arizona.

Inasmuch as fatigue can be defined as "... a failure to maintain the required or expected force" (Edwards, 1982), there are several sites between the command (supraspinal) and effector (muscle) centers at which this failure can occur. Among these are axonal-branch-point and neuromuscular-junction transmission failure. These aspects of fatigue were examined by comparing the force elicited in the soleus (n = 5) and medial gastrocnemius (n = 3) muscles of Sprague-Dawley rats (3.1-4.8 N) by nerve and direct-muscle stimulation before and after a fatigue test (6 min of 1 Hz trains with each train lasting 330 ms and including 13 stimuli; Burke et al., 1971). There was no difference in the mean peak twitch force obtained by nerve and direct-muscle stimulation before the fatigue test; the nerve-elicited values were 97.9 ± 5.9% of those obtained by direct-muscle stimulation. In contrast, this ratio was 77.9 ± 19.9% after the fatigue test. This post-fatigue test difference in the peak twitch force produced by nerve and direct-muscle stimulation was not muscle-dependent (soleus 16.5 ± 11.9%, medial gastrocnemius 31.3 ± 29.8%) but rather was correlated significantly (r² = 0.89, p < .05) with the amount of fatigue (i.e., force reduction) exhibited during the fatigue test. These data underscore a neural contribution to whole-muscle fatigue in animals without neuromuscular lesions.


A quantitative approach is being used to assess the relationship between neuromuscular physiology and biochemical properties using enzyme histochemistry. Following collection of physiological data on single motor units of the tibialis posterior muscle of adult cats and glycerol depilation of the dissected muscle unit, transenergized sections of muscle were stained for periodic acid Schiff and myokinase ATPase; alternate serial sections were lyophilized. Fibers of the muscle unit identified histologically were dissected from the lyophilized sections and analyzed biochemically using microanalytical techniques.

Biophysical and biochemical data were, thus, obtained on the same fast-contracting fast-fatiguing motor units: small and large in the cat.

Table 1. Physiological Characteristics of Motor Units

<table>
<thead>
<tr>
<th>Motor Unit Type</th>
<th>Motor Unit Velocity</th>
<th>Twitch Time</th>
<th>Tension Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>7.5 1.9</td>
<td>1.7 0.8</td>
<td>0.8 0.1</td>
</tr>
<tr>
<td>Large</td>
<td>13.0 3.0</td>
<td>2.8 1.2</td>
<td>1.5 0.3</td>
</tr>
</tbody>
</table>


This project addressed the effects of cage size on muscle properties with the assumption that cage size influences the degree of activity. A total of 24 SD weanling rats were housed in either a small FDA-approved laboratory cage (2/cage) or one 474x larger (15/cage). Subsequently, some contractile, electrical, and fatigue characteristics were determined in two sets of rats (10-SO, 16-SO, respectively). Rat gastrocnemius muscle (EDL) and soleus (SOL) muscles characterized as predominately fast-contracting ('fiber-type' distribution approximately 3%-SO, 97%-FOG) and slow-contracting (80%-SO, 16%-FOG, respectively) (Ariano et al., J. Histochem. Cytochem. 21: 31, 1973). The results included in test 1.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Force</th>
<th>Fatigue</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOL</td>
<td>1.00</td>
<td>0.90</td>
</tr>
<tr>
<td>EDL</td>
<td>0.96</td>
<td>0.89</td>
</tr>
</tbody>
</table>


As an assessment of cage-size effects on the electromyogram (EMG), we have monitored the compound muscle action potential (AP) during fatigue in the EDL muscle of rats in which the small cage is maintained and calculated the various parameters of 2474 EMG EMG. These parameters include the absolute onset of action potential (AP) duration during the fatigue test for all groups of rats. The changes exhibited by SOL were gradual, with final 60 min values of 92% and 103% of the small- and large-cage groups, respectively, that were not significantly different. In contrast, EDL exhibited a greater increase in AP duration at 2 min (p < 0.05) and maintained values at 6 min (p < 0.05) compared with values at 1 min. SOL values were comparable for the two muscles. The changes in force and muscle weight, however, appeared to be muscle specific: the large-cage rats developed a greater maximum force in SOL and a lesser normalized muscle weight for EDL.

Supported by grants from NASA (NAG3-338) and NIH (HL02749).

226.8 EFFECT OF "DISUSE" ON MAMMALIAN FAST-TWITCH MUSCLE: JOINT FIXATION COMPARED TO NEURALLY APPLIED TTX. D. St-Pierre, J. D. Fournier, and P. Gardiner (SPON: A. Paterson). Sciences de l'activité physique, Univ. de Montréal, Québec, H3C 3J7.

The effect of "disuse" on the functional properties of fast-switch (FT) mammalian muscle is controversial, perhaps since the various "disuse" models reduce activity to different extents, and may introduce factors other than reduced activity. Our goal was to compare the effects of "disuse" produced by neuromuscular blockade (TTX) and joint fixation on the atrophic and contractile responses of Che joints were fixed for 2 weeks according to Fournier et al. (1983) and the paralysis maintained for 2 weeks. In a separate group of rats left knee and ankle joints were fixed for 2 weeks according to Fournier et al. (Exp. Neurol., 1983).

Muscle weights and in situ contractile properties are summarized below. Joint fixation produced a decrease in muscle wet weight and absolute tectonic tension. The degree of atrophy was more severe with TTX-disuse and was accompanied by a decrease in tensional tension per unit muscle weight (F/G). In addition, TTX-disuse resulted in an elevation of twitch tension ratio, a prolonged twitch, and an increased degree of fusion at 50 Hz. The normalized maximal rate of tension development (stress) was highest in the TTX group. Fatigue resistance was highest in 

Table 2. Contractile Properties of Che Joints

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force: initial</td>
<td>3.45 kg</td>
</tr>
<tr>
<td>Max. force: initial</td>
<td>5.0 kg</td>
</tr>
<tr>
<td>Relaxation time: initial</td>
<td>2 sec</td>
</tr>
</tbody>
</table>

Significant differences between groups are indicated by asterisks (p < 0.05) and by boldface type (p < 0.01). The data suggest that complete disuse of mammalian FT muscle causes atrophy, slowing of contractile speed and a loss in contractile strength per unit muscle weight, and are consistent with a loss of sarcoplasmic reticular function and of myofibrillar protein degeneration with disuse.
In an attempt to identify the mechanisms associated with the decline in force during a standardized fatigue test (Burke et al., J. Physiol. 235; 12, 1973), we have monitored, in vivo, the compound muscle action potential (AP) and the isometric force during a 6-min test in which the test muscle was activated by supramaximal intermittent stimulation of its nerve. Accordingly, the soleus (SOL) and extensor digitorum longus (EDL) muscles of male and female SD rats (1.36 and 2.65 N, respectively; 120-130 days) were subjected to a protocol that included 1 Hz trains of 13 stimuli delivered at a rate of 40 Hz. The APs were recorded with a pair of intramuscular stainless-steel electrodes and were quantified by average measurements of the area and "mean" amplitude (MA) for the 13 APs within each train (Stuart et al., Proc. XXIV IUPS XV; 190, 1983). The fatigability of the muscles was quantified by a measure of fatigue resistance (FR) peak tetanic force at 6 min relative to initial force.

To raise the rats in small and large cages, the FR of both test muscles extended over a range of values such that the muscles clustered within each FR group of relative high, intermediate, and low FR: for SOL, these values (X ± SD) were 112.7 ± 10, 92.6 ± 7, and 67.2 ± 8 (n = 5), respectively, while for EDL, the values were 42.5 ± 6 (n = 3), 32.5 ± 2 (n = 3), and 10.7 ± 6 (n = 2), respectively. Despite these differences in FR for EDL, the 3 groups exhibited a qualitatively similar relationship between AP area and force, but not relative to the course of the fatigue test. In all 3 groups, the relationship was characterized by an initial potentiation and a subsequent parallel decline in both AP area and force. Quantitatively, however, the high FR group displayed the greatest potentiation of both force and AP area. Somewhat similar relationships were apparent between MA and peak force for EDL, although MA did not plateau initially at 6 min. The areas and MA during the test were similar for SOL (r² = 0.83, p < 0.1). In contrast, the high and intermediate FR groups demonstrated a markedly different area-force relationship than the low FR group in that force essentially remained constant while peak force declined for the low FR group. In addition, the changes in AP area and MA for SOL, while significant (p < 0.01), were less related (r² = 0.35) than for EDL.

It was apparent that under these conditions (also Sandercock et al., J. Appl. Physiol: 58, 1073, 1985) both AP area and MA changed during the course of the fatigue test. However, we did not consider our test as to whether these AP changes reflect a change in the force-generating capacity of the muscle fibres due to muscle fatigue, due to the activity of the individual fibres, or a combination of both mechanisms.

Supported by grants from NASA (NAGW 338) and NIH (HD0729).


The mechanisms responsible for the fatigue and long duration muscle fatigue has been studied utilizing simultaneous measurements of 31N Nuclear Magnetic Resonance spectroscopy, surface rectified integrated EMG(RIDG) and force from FR motor units. During a four minute maximum isometric contraction to produce muscle fatigue, pH fell from 7.1 to 6.4, phosphocreatine fell to undetectable levels, and mean maximum force fell to 58% of the initial force (1976). Twitch muscle potentiation (post P/A pre P/A) was 60% in the fresh muscle, less than 25% after fifteen minutes of recovery from fatigue with gradual return toward baseline levels over a time course that paralleled that of ME. Similarly, the response to low frequency stimulation recovered more slowly (65% of control within 21 minutes of recovery) than the response to high frequency stimulation which was near baseline (93% recovery by twenty minutes of recovery). These observations support our hypothesis that long duration fatigue is independent of muscle pH and inorganic phosphates.

A persistent impairment of excitation-contraction coupling is likely based on these observations.

Supported by grants from NASA (NAGW 338) and NIH (HD0729).

ENDURANCE TIME CHARACTERISTICS OF THE DORSIFLEXORS AND PLANTARFLEXORS MUSCLES OF THE HUMAN ANKLE. A. Vahid Shahidi, R. E. Kearney and J.V. Hunter (SPOM: B. Gallana). Biomedical Engineering Unit, Faculty of Medicine, McGill University, Montreal, Quebec, Canada, H3G 1Y6.

Neuromuscular fatigue may be defined as any reduction in the force generating capacity of muscle due to fatigue. The present study was undertaken to determine the rate of neuromuscular fatigue during low level contractions in the ankle dorsiflexors and plantarflexors. The endurance time was defined as the time at which the ankle torque first dropped below 95% of the target level.

The figure shows endurance time as a function of contraction level for both plantarflexing (triangles) and dorsiflexing (squares) contractions for a typical subject. Endurance time decreased with increasing contraction level in an approximately exponential manner. Indeed, the simple exponential model fitted to the data provides a good fit; the variance accounted for by this model was always greater than 97.32 for the 8 subjects studied to date. The excellent quality of the fits obtained is shown by the similarity of the slopes of the individual experiments and the exponential (predicted) values in the figure.

Supported by a grant from the Canadian Medical Research Council.

In the human caudate, we examined the topography of somatostatin (SS), neuropeptide Y (NPY) and NADPH-diaphorase (NADPH-D) neurons in human caudate and their relationships to zones of different acetylcholinesterase (AChE) activity (striosomes). Twelve blocks of serial sections (100um) were incubated in a neutral buffered formalin at 4°C for 48 hours. Sections were incubated with antisera to SS and NPY followed by amplification and detection using an avidin-biotin peroxidase method or indirect immunofluorescence. Absorption controls were consistently negative. NADPH-D staining was performed on sections reacted with NADPH-D stain and counterstained with Triton X-100 (0.8%) and monosodium maleate (125mM) to the incubation medium. These modifications enhanced sensitivity and allowed detection of fainter NADPH-D positive pattern of neuropil staining. Large numbers of reactive neurons were uniformly distributed throughout the caudate in bands and clumps which avoided zones of low AChE activity. This was especially striking in AChE, where background staining was limited to the striosome mosaic was modified in the nucleus accumbens where the ellipsoidal or serpiginous low AChE patches were flattened and oriented into a series of horizontal bands. Colocalization studies, including double immunofluorescence, showed that SS, NPY, and NADPH-D activities coexist in a single population of neurons in human striatum. The morphology of these neurons was variable and could be divided into 4 categories which are typical of aspiny type interneurons. The conduction velocity (CV) measurement is an important parameter in determining the properties of axonal units. The purpose of this investigation was to evaluate methods of determining CV of motor axons and to establish the reliability of the CV technique. Single motor axons to the functionally isolated tibialis posterior (TP) muscle in the hindlimb were activated by suprathreshold stimulation of cut ventral-root (VR) filaments. Action potentials evoked in the TP muscle-nerve were recorded extracellularly from bipolar electrodes at the popliteal fossa level. CV measurements were made from VR to muscle-nerve (conventional CV) and between proximal and distal pairs of muscle-nerve electrodes (muscle-nerve CV). The comparison of CV measurements revealed that the muscle-nerve CV was 3.75 slower, on average, excluding corrections for stimulus utilization time, than the conventional CV estimate. Considerable variability was observed as well as differences in stimulus utilization time, variable muscle branching, and variability in regional CV. The variabilities inherent in distance and time measurements were estimated by making multiple measurements of these parameters. The result also accounted for much of the variability in measured values of conventional and regional CV's. These data indicate that uncertainties in the time and distance measurements account for most, but not all, of the variability of CV estimates in the tibialis posterior. The results suggest that interlaboratory differences in CV estimates which were not accounted for by any error estimates. 

63.24 FATIGUE-RELATED CHARACTERISTICS OF THE SOLEUS AND EDL MUSCLES IN SMALL AND LARGE CAGE-REARED FEMALE RATS. K.A. Vo1, L.L. Rankin, R.M. Enoka, and D.G. Stuart. Dept. of Physiology and Exercise & Sport Sciences, University of Arkansas, Fayetteville, AR 72701.

Previous studies from this laboratory (Enoka et al., and Rankin et al., Soc. Neurosci. Abstr. 10: 781, 1984) have indicated that the soleus (SOL) and extensor digitorum longus (EDL) muscles are affected by the size of the cage in which the animal was raised. To continue our investigation into cage-size effects, we have examined some histochemical and fatigue-related characteristics in female hindlimb muscles. Female SD weaned rats were raised for 100-135 days in either a small (SA)- or large (SA)-case. A total of 25 rats were raised in small and 25 in large cages. Subsequently, fatigue-related characteristics were determined in vivo for the muscles SOL and EDL. To continue our investigations, we have examined some histochemical and fatigue-related characteristics in female rat hindlimb muscles. Female SD weaned rats were raised for 100-135 days in either a small (SM)- or large (SM)-case. A total of 25 rats were raised in small and 25 in large cages. Subsequently, fatigue-related characteristics were determined in vivo for the muscles SOL and EDL. 

The results indicate that, in contrast to our studies using male rats, the fatigue resistance of SOL and its innervating female rats was not significantly affected by cage size. In addition, cage size did not significantly affect the histochemical composition of either SOL or EDL. In order to reduce the effects of fatigue-related characteristics in female rat hindlimb muscles.

64.1 VARIABILITY OF ADOPTINAL CONDUCTION VELOCITY MEASUREMENTS IN HUMAN MOTOR UNITS. R.A. Gordon, R.N. Hand, R.M. Rankin, R.M. Enoka, and D.G. Stuart. Dept. of Physiology and Exercise & Sport Sciences, University of Arkansas, Fayetteville, AR 72701.

The conduction velocity (CV) measurements are an important parameter in determining the properties of axonal units. The purpose of this investigation was to evaluate methods of determining CV of motor axons and to establish the reliability of the CV technique. Single motor axons to the functionally isolated tibialis posterior (TP) muscle in the hindlimb were activated by suprathreshold stimulation of cut ventral-root (VR) filaments. Action potentials evoked in the TP muscle-nerve were recorded extracellularly from bipolar electrodes at the popliteal fossa level. 

The variabilities inherent in distance and time measurements were estimated by making multiple measurements of these parameters. The result also accounted for much of the variability in measured values of conventional and regional CV's. These data indicate that uncertainties in the time and distance measurements account for most, but not all, of the variability of CV estimates in the tibialis posterior. The results suggest that interlaboratory differences in CV estimates which were not accounted for by any error estimates.
CAGE-SIZE AND GENDER EFFECTS ON FATIGUE IN RATS

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University of Arizona
Tucson, AZ 85721

As a biological tissue, muscle adapts to the demands of usage. One traditional way of assessing the extent of this adaptation has been to examine the effects of an altered-activity protocol on the physiological properties of muscles. However, in order to accurately interpret the changes associated with an activity pattern, it is necessary to employ an appropriate control model. There exists a substantial literature which reports altered-use effects by comparing experimental observations with those from animals raised in small laboratory cages (e.g., 9, 10). Accumulating evidence suggests that small-cage-reared animals actually represent a model of reduced use. For example, laboratory animals subjected to limited physical activity have shown resistance to insulin-induced glucose uptake which can be altered with exercise training (3). Similarly, in male rats such parameters as body mass, muscle mass, fatigue resistance, and muscle-relaxation characteristics have been shown to be affected by cage size (8). Furthermore, during the course of this project it appeared that the cage-size effects were confounded by a gender effect. This report further examines these issues by considering the effects of cage size during rearing and of gender on the physiological properties of adult rat muscle.

METHODS

Adult (100-135 days old) male and female Sprague-Dawley rats were raised in separate groups from weaning age (21 days) in either of two cage sizes. The small cages (47 x 23 x 20 cm) each contained 3-9 rats while there were 6-7 animals, separated by gender, in each of the two large cages (320 x 183 x 99 cm). The large cages provided approximately 133x more surface area (floor + 4 walls). There were 6-7 rats in each of the 4 groups; namely, small-cage males, large-cage males, small-cage females, large-cage females.

The two test muscles were soleus and extensor digitorum longus (EDL). Soleus is a slow-contracting, antigravity, plantarflexor muscle which comprises about 94% type SO and 16% type FOG muscle fibers (1). In vivo electromyographic (EMG) recordings reveal constant motor-unit recruitment while the animal is awake (6). In contrast, EDL is a fast-contracting, non-weight-bearing, dorsiflexor muscle with a fiber-type distribution of about 8% SO, 57% FOG, and 37% FG (1). EMG recordings show that EDL is silent when the animal is at rest and activated phasically during locomotion (6).

In terminal experiments, with the rats under deep barbiturate anesthesia, the soleus and EDL muscles were surgically isolated and maintained in a paraffin-filled muscle bath at a temperature of 36°C. The following experimental protocol was used: 32 twitches were elicited by stimulation through the nerve to evaluate treppe; 1 single tetanus at 100 Hz for 500 ms to determine the peak force; a standardized fatigue test (2) which involved intermittent stimulation (40 Hz) of the nerve with trains of 13 stimuli, each train lasting 330 ms and occurring once each second; 8 twitches to evaluate post-tetanic potentiation; and finally, two 100 Hz tetani. Force was measured using a force transducer to which the tendon of the test muscle was attached via a low-compliance dacron line. The compound muscle action potentials generated by the stimuli were recorded with a pair of intramuscular stainless-steel wire electrodes. The 13 action potentials associated with each train of stimuli during the fatigue test were averaged and quantification was based on the average waveform. Measurements on the average waveform were made of area relative to the isoelectric line and of peak-to-peak amplitude. Statistical differences were assessed with a t-test for two means.

RESULTS

It is well documented that male rats are larger than the females of a similar age (7). This is apparent in Table 1 in the measurements of whole-body and test-muscle mass in that the female values averaged 67% of those for the males. These size differences, however, were not affected by cage size since within each of the 4 animal groups the mass of the two test muscles was not different; the average values for soleus and EDL were 0.23 and 0.25 g for the males and 0.17 g for both muscles in the females.

Qualitatively similar trends were apparent in the absolute force data in that there was no cage-size effect, but there was a partial gender effect. That is, the peak force exerted by EDL in response to a 330-ms train of 40 Hz stimuli was greater in males (X = 2.13 N) than females (X = 1.29 N). When the EDL force measurements were normalized relative to test-muscle mass, however, this difference disappeared. In contrast, the absolute 40 Hz force exerted by soleus was not affected by cage size or gender despite gender differences in soleus mass. However, normalization of soleus force did reveal a cage-size effect in that the force exerted per unit muscle mass of the small-cage males (6.0 N/g) was significantly less than the value for the large-cage males (7.9 N/g).

In addition to these measures of size and force, the ability of the test muscles to sustain activity was also examined. The 4 measurements used to characterize this capability were fatigue index (FI), relaxation time, area and amplitude of EMG. These 4 parameters are used as indices of contractile fatigue (FI; 2), the "energy-state" of the muscle (relaxation time; 4), and precontractile fatigue (EMG; 3). The test muscles were subjected to a standardized fatigue test, and the 4 measures were made at selected intervals throughout the test; the final values are reported in Table 1. There were no cage-size effects among any of these parameters for the test muscles of the female rats. In contrast, the males exhibited 3 differences: (1) a cage-size effect for the FI of soleus; (2) a gender effect for the FI of the large-cage rats; (3) a combined (cage-size and gender) effect for the EMG area of small-cage EDL. Taken together, these results suggest that male rats are more sedentary in the small cages (decreased normalized muscle force and FI for
Table 1. An overview of the effects of cage size during rearing and of gender on size, contractile, and electromyographic (EMG) characteristics of the test muscles.

<table>
<thead>
<tr>
<th></th>
<th>Whole Muscle</th>
<th>Absolute Muscle Force</th>
<th>Relative To Muscle Mass</th>
<th>Fatigue Index</th>
<th>Relaxation Time</th>
<th>Area</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Cage:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male:</td>
<td>449 ± 1</td>
<td>1.42 ± 1</td>
<td>6.08 ± 1</td>
<td>898 ± 45</td>
<td>96 (12)</td>
<td>103</td>
<td>81 (25)</td>
</tr>
<tr>
<td>Soleus</td>
<td>0.260 ± 0.03</td>
<td>(1.8)</td>
<td>(21)</td>
<td>(17)</td>
<td>(8)</td>
<td>(19)</td>
<td>(25)</td>
</tr>
<tr>
<td>EDL</td>
<td>0.260 ± 0.03</td>
<td>(1.8)</td>
<td>(21)</td>
<td>(17)</td>
<td>(8)</td>
<td>(19)</td>
<td>(25)</td>
</tr>
<tr>
<td>Female:</td>
<td>260 ± 10</td>
<td>(1.7)</td>
<td>(1.5)</td>
<td>(16)</td>
<td>(22)</td>
<td>(18)</td>
<td>(37)</td>
</tr>
<tr>
<td>Soleus</td>
<td>0.170 ± 0.01</td>
<td>(1.9)</td>
<td>(18)</td>
<td>(12)</td>
<td>(14)</td>
<td>(15)</td>
<td>(15)</td>
</tr>
<tr>
<td>EDL</td>
<td>0.170 ± 0.01</td>
<td>(1.9)</td>
<td>(18)</td>
<td>(12)</td>
<td>(14)</td>
<td>(15)</td>
<td>(15)</td>
</tr>
<tr>
<td>Large Cage:</td>
<td>430 ± 10</td>
<td>(1.7)</td>
<td>(1.3)</td>
<td>(18)</td>
<td>(12)</td>
<td>(14)</td>
<td>(15)</td>
</tr>
<tr>
<td>Male:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soleus</td>
<td>0.220 ± 0.02</td>
<td>(1.1)</td>
<td>(13)</td>
<td>(12)</td>
<td>(23)</td>
<td>(40)</td>
<td>(40)</td>
</tr>
<tr>
<td>EDL</td>
<td>0.220 ± 0.02</td>
<td>(1.1)</td>
<td>(13)</td>
<td>(12)</td>
<td>(23)</td>
<td>(40)</td>
<td>(40)</td>
</tr>
<tr>
<td>Female:</td>
<td>271 ± 10</td>
<td>(1.7)</td>
<td>(1.3)</td>
<td>(18)</td>
<td>(12)</td>
<td>(14)</td>
<td>(15)</td>
</tr>
<tr>
<td>Soleus</td>
<td>0.160 ± 0.02</td>
<td>(0.9)</td>
<td>(16)</td>
<td>(16)</td>
<td>(18)</td>
<td>(18)</td>
<td>(18)</td>
</tr>
<tr>
<td>EDL</td>
<td>0.170 ± 0.01</td>
<td>(1.8)</td>
<td>(15)</td>
<td>(9)</td>
<td>(10)</td>
<td>(10)</td>
<td>(10)</td>
</tr>
</tbody>
</table>

a Peak force at 40 Hz; b Ratio of the peak 40 Hz force at 6 min relative to the initial value. The protocol involved a standard fatigue test (Burke et al., 1973); c Difference in the time for the force to decline to 20% of the peak force at the end of the fatigue test (6 min) relative to the initial tetanus; d Values expressed relative to measurements on the initial average action potential; e Values are X (±SD); f p < 0.05 between males and females; g p < 0.05 between small and large cage soleus and more active in the large cages (increased soleus FI).

CONCLUSIONS
1. Cage size and gender had minimal effects on changes in the EMG measures.
2. Gender affected whole body mass, test muscle mass, and absolute force.
3. Cage size and gender affected normalized force and fatigability.
4. Since the cage-size effects were only present in the male rats, these results suggest caution in the interpretation of results based on this animal model.

REFERENCES