Mechanical properties of smooth muscle.
I. Length-tension and force-velocity relations

ALLEN R. GORDON AND MARION J. SIEGMAN
Department of Physiology, Jefferson Medical College, Thomas Jefferson University, Philadelphia, Pennsylvania 19107

THE MECHANICAL PROPERTIES of skeletal and cardiac muscles are well defined. Unfortunately, very little is known about smooth muscle, and often the behavior of smooth muscle is explained on the basis of the properties of the two other muscle types. The paucity of systematic studies of the mechanical properties of smooth muscle may be due to many complicating characteristics not found in skeletal muscle. Anatomically, visceral smooth muscle is arranged in two independently contracting layers, oriented in different directions and separated by an intrinsic nervous system. Many smooth muscles have nonparallel arrangements of cells. The ability of some smooth muscles to contract spontaneously not only leads to difficulty in interpreting the effects of stimulation, but also masks the passive reference tension from which active tension is measured. Further complicating factors are the viscous behavior of resting smooth muscle, which, when stretched to a fixed length or when placed under a constant load, exhibits the phenomena of stress relaxation and creep, respectively. The ability of some smooth muscles to actively contract in response to stretch is also well known.

Within the last 2 decades, several investigations of the mechanical properties of smooth muscle have been reported. In all of these studies, a wide variety of experimental methods have been used for stimulation and for the control of spontaneous activity which seriously affect interpretation and, particularly, quantification of the results. Briefly, these methods involve the use of longitudinal a-c stimulation (3, 10-12, 24-26), which does not yield maximum contraction (22, 34), and/or the inclusion of metabolic poisons and drugs, singly or in combination, in the bathing medium in order to eliminate spontaneous activity (3, 23, 26, 27), which, themselves, alter the contractility of the tissue (26). Comparisons are further complicated by the many different types of smooth muscle studied.

Qualitatively, the length-tension relationships of various types of smooth muscle are similar to striated muscle: rabbit uterus (11, 12, 14), guinea pig taenia coli (3, 9, 26), vascular (23, 32, 33), canine trachealis (35), and feline intestine (27). These studies have shown that smooth muscles exhibit an optimum length (l0) for tension development. Smooth muscles are also capable of tension development over an extremely wide range of muscle lengths, that is, some tension can be developed at muscle lengths as low as 20-30% of l0. The maximum active tetanic tension, P0, is generally less than striated muscles, and ranges from 0.13 kg/cm² cross section for uterus (12) to approximately 2 kg/cm² cross section for vascular smooth muscle (23). The relative amount of passive tension present in smooth muscles at l0 is variable. Some investigators reported little or no passive tension at l0, while others found appreciable passive tension. The discrepancies may be attributed to actual differences in the mechanical properties of the various types of smooth muscle, or to differences in experimental techniques. In addition to the problems introduced by methodology already cited, there is much confusion regarding the effect of temperature on passive and active mechanical properties (9, 12, 14) of smooth muscle which has not yet been resolved.

Smooth muscles show the same type of hyperbolic relationship between the force and maximum velocity of shortening as does striated muscle (3, 12, 21, 35). The velocities of shortening of smooth muscle are generally much less than skeletal muscle. For the most part, this difference is reflected by lower values of the constant b from the Hill equation (18). While no thermodynamic data are available for isotonic contractions of mammalian smooth muscle, the low value of b is consistent with the low rate of metabolism of smooth muscle (7).

Because many of the discrepancies regarding the passive and active mechanical properties of smooth muscle may be based on experimental technique, it appeared to us that the entire problem was worthy of reinvestigation. In the present study, the length-tension and force-velocity relationships of the rabbit taenia coli were examined under conditions in...
which spontaneous mechanical activity was eliminated and the integrity of the preparation was preserved, so that quantification of the results could be made with reasonable confidence. A preliminary report of these results was presented earlier (16).

**Methods**

**Preparation of Tissues and Solutions**

Female rabbits (white New Zealand strain), weighing 1.9-2.4 kg, were sacrificed by cervical fracture. The taenia coli was isolated from the cecum, taking care to avoid stretching the muscle segment. A muscle strip, about 3 mm wide, was mounted in stainless steel clamps. The length of the preparation, taken as the distance between the clamps, was 5 mm. The muscle was mounted in a Plexiglas chamber containing a flowing, oxygenated Krebs-bicarbonate solution, and allowed to equilibrate under 2 g tension for 2 hr at 22 C. After the experiment, the muscle was cut from the clamps and weighed on a Roller-Smith torsion balance to the nearest 0.2 mg.

One end of the muscle was connected to an isometric force transducer (Grass model FT-10) and the other to the armature shaft of a large galvanometer (Grass oscillograph). Two micrometer stops were used to adjust the muscle length or limit the excursion of the armature. Muscle loading was accomplished by passing a current through the armature coil from a constant-current source (Grass CCU-1). In this manner, the muscle could be held at a fixed length with an afterload. The velocity of shortening was proportional to the back electromotive force generated by the moving galvanometer coil. Recordings were made on a Grass model 5 or model 7 polygraph.

The muscles were electrically stimulated from two platinum-platinum chloride electrodes placed 5 mm apart on either side and parallel to the longitudinal axis of the muscle segment. In order to tetanize the muscle, 10 V rms, 60 Hz, a-c stimulation was used.

Temperature regulation was accomplished by means of a thermoelectric cooling module (Cambion 3951), which was powered by a modified a-c proportional controller (RFL rms, 60 Hz, a-c stimulation was used. Muscle stretching the muscle segment. In order to tetanize the muscle, 10 V

**Experimental Procedures**

**Length-tension determinations.** After the equilibration period, the muscle length was reduced to a length at which the tension was less than 25 mg. This length was denoted $l_o$. To determine the total tension ($P_t$), the muscle was tetanically stimulated, after which its length was increased by 0.5 mm. Following a recovery period of 15 min, the muscle length was quickly reduced by 0.25 mm to facilitate stress relaxation. In some preparations, a biphasic change in tension occurred, which is shown in Fig. 1. The minimum tension was taken as the passive tension ($P_p$) for the new muscle length. The above procedure was repeated, giving the passive and total tension for a series of muscle lengths.

The active tension ($P$) was taken as the difference between $P_t$ and $P_p$ at each setting of muscle length. The length at which maximum active tension ($P_{ma}$) was observed was denoted $l_o$ (29). The tensions $P_p$ and $P$ were normalized to the total muscle tension at $l_o$. The muscle lengths were also normalized to $l_o$.

**Force-velocity determinations.** The isotonic force-velocity relationship was determined at initial muscle lengths $l_o$ and $l_w$. The preparation was afterloaded by a force no less than the resting passive tension and subsequently at increments of 0.5 g. Muscles were stimulated tetanically, and the active tension and the velocity of shortening were recorded.

**Cross-sectional area.** The cross-sectional area of each muscle was calculated from the equation $A = M/pL$, where $M$ is mass (g), $p$ is the density (g/ml) and numerically equal to the specific gravity, and $L$ is the length (cm). The specific gravity of tissues bathed in Krebs-bicarbonate solution, as determined by pycnometric technique, was 1.056 ± 0.002 (mean ± SE; $n = 7$). Statistical analysis. Statistical analyses for significance in differences were made on the basis of set or pair comparisons using the Student $t$ test. A least-squares regression analysis was made to obtain the force-velocity constants.

**Results**

**Relationship Between Muscle Length and Tension**

The isolated taenia coli, like other single-unit smooth muscles, exhibits spontaneous mechanical activity when bathed in a physiological salt solution at 37 C. The presence of spontaneous mechanical activity makes it impossible to distinguish the passive and active mechanical properties of a muscle. For this reason, it was essential to seek some condition which would reduce or eliminate the spontaneous activity without interfering with the integrity of the tissue. Axelsson and Bulbring (5) showed that the spontaneous electrical and mechanical activity in taenia coli can be...
were therefore performed at this temperature. Accordingly, the bath temperature was reduced until no spontaneous mechanical activity was observed. At 22°C the muscles appeared to be atonic, and all experiments were therefore performed at this temperature.

Maximum tetanic tension was dependent on the duration of stimulation up to durations of 30–35 sec, and the half-time-to-peak tension was about 7 sec. The decay of tension upon cessation of stimulation occurred with a half-time of about 15 sec. The tetanic tension developed with 60 Hz, 10 v rms stimulation was comparable, within 1%, to tensions developed during exposure to high potassium concentrations (100 mM KCl replacing NaCl of medium) or acetylcholine (2 x 10⁻⁵ g/ml).

The relationship between length and tension is shown in Fig. 2. At the optimal length 1₀, for tension development, appreciable passive tension was observed. An estimate of residual spontaneous activity at muscle length 1₀, epinephrine was added to the bathing medium. Epinephrine abolishes the spontaneous electrical and mechanical activity in taenia coli at all degrees of stretch at temperatures ranging from 20 to 36°C (8, 9). Some preparations exhibited a biphasic response following the reduction in muscle tone was only 100 mg, less than 2% of the active tension. In other preparations, the response upon reduction in length was monotonic, and epinephrine had no effect even when the dose was doubled. These results indicate that the muscles were essentially atonic at 22°C, and the minimum tension could be taken as the passive tension for a given muscle length. The total exposure time to epinephrine during the test was 100–200 sec. Care was taken to wash out the drug to avoid the introduction of a new variable which might affect contractility.

As shown in Fig. 2, the passive tension rises monotonically with length and is 30% of the total tension at 1₀. The active tension at the length 1.05 1₀ is significantly lower than the maximum active tension at 1₀ (P = 0.029). The maximum active tension, in kilograms per square centimeter cross section, at length 1₀ was calculated by dividing the maximum active tension, in grams, by the cross-sectional area giving a mean (±SEM) value of 0.89 ± 0.11.

**Relationship Between Force and Maximum Velocity of Shortening**

Records from a typical experiment showing the velocity of shortening and the active tension of a tetanized muscle at two different loads appear in Fig. 3. The relationship between the maximum velocity of shortening and the load, determined at the initial length 1₀, is shown in Fig. 4. The velocity of shortening of taenia coli varies inversely with the load.

To test the hypothesis that the relationship between the load, P, and the maximum velocity of shortening, v, was hyperbolic and conformed to the equation derived by Hill (18), where

\[
(P + a)(v + b) = (P₀ + a)b \tag{1}
\]

the data were replotted as P vs. \((P₀ - P)/v\) according to a rearranged form of the Hill equation:

\[
P = \frac{b(P₀ - P)}{v} + a \tag{2}
\]

**FIG. 3.** Determination of maximum velocity of shortening. Upper tracings are muscle load and lower tracings are velocity of shortening. Arrows indicate onset of stimulation. Maximum velocity of shortening is taken as peak of velocity record for each load (note calibrations). In A, load was 0.1 g and maximum velocity of shortening was 0.095 mm/sec. In B, load was 1.4 g and maximum velocity of shortening was 0.033 mm/sec.

**FIG. 4.** Determination of force-velocity constants. Open circles show data from a typical experiment, plotted as load or developed tension (ordinate) vs. maximum velocity of shortening (abscissa). Data are replotted (filled circles) as P vs. \((P₀ - P)/v\). Slope and intercept of regression line (through filled circles) are constants b and a, respectively. Hill equation is plotted using values for constants and is represented by line through open circles.

**TABLE 1.** Force-velocity constants. Open circles show data from a typical experiment, plotted as load or developed tension (ordinate) vs. maximum velocity of shortening (abscissa). Data are replotted (filled circles) as P vs. \((P₀ - P)/v\). Slope and intercept of regression line (through filled circles) are constants b and a, respectively. Hill equation is plotted using values for constants and is represented by line through open circles.
A regression line was fitted to these data points with a high degree of correlation ($r = 0.97$), and is shown in Fig. 4. The constants from the Hill equation, $a$ and $b$, are numerically equal to the intercept and slope, respectively, of the regression line. The Hill equation was plotted using the values of $a$ and $b$ so obtained and is in good agreement with the experimental data. In addition, the maximum velocity of shortening at zero load, $V_{\text{max}}$, was calculated from the Hill equation where:

$$V_{\text{max}} = \frac{P}{b/a}$$

A similar procedure was followed when the force-velocity relationship was determined at the initial length $l_i$. The values obtained for the various force-velocity constants are listed in Table 1.

Normalized constants for each muscle were obtained from a normalized form of the Hill equation:

$$\left[ \frac{P}{P_{\text{o}l}} + \frac{a}{P_{\text{o}l}} \right] \left[ \frac{V}{l} + \frac{b}{l} \right] = \left[ 1 - \frac{a}{P_{\text{o}l}} \right] \left[ \frac{b}{l} \right]$$

where $P_{\text{o}l}$ is the maximum active tension for a given length, following the notation of Abbott and Wilkie (1). The muscle length is represented by $l$. At length $l_o$, $P_{\text{o}l} = P_o$. This equation can be rearranged to the linearized form:

$$\frac{P}{P_{\text{o}l}} = \frac{b}{l} \left[ 1 - \frac{P}{P_{\text{o}l}} \right] \left[ \frac{V}{l} \right] - \left[ \frac{a}{P_{\text{o}l}} \right]$$

for the determination of the normalized constants $a/P_{\text{o}l}$ and $b/l$. The normalized maximum velocity of shortening is obtained from the normalized Hill equation by setting $P/P_{\text{o}l} = 0$, and

$$V_{\text{max}}/l = \frac{b/l}{a/P_{\text{o}l}}$$

In the determination of the dynamic constants, the correlation coefficient of the regression line was greater than 0.967 for all experiments.

To test for dependence on initial muscle length, the differences of the means of the constants at the two initial lengths were tested for significance. It is apparent that the constants $a$, $b$, $a/P_{\text{o}l}$, $b/l$, and $V_{\text{max}}/l$ are not significantly changed by varying the initial length of the muscle. Therefore, the respective values for all experiments were combined, and the means are also listed in Table 1.

The Hill equation was calculated and plotted for the initial lengths $l_i$ and $l_o$ using the respective values of $P_{\text{o}l}$ and the combined mean values of $a$ and $b$ (Fig. 5). The effect of decreasing the initial muscle length is a shift of the force-velocity curve toward the origin with a corresponding change in the intercepts $P_{\text{o}l}$ and $V_{\text{max}}$.

**DISCUSSION**

**Length-Tension Relation**

The presence of spontaneous tone precludes the determination of passive and active mechanical characteristics of a muscle. Taking advantage of the fact that a small reduction in temperature can reduce the excitability of taenia coli sufficiently to eliminate spontaneous electrical discharge, an atonic preparation was readily obtained. This method obviates the use of chemicals and drugs whose effects on contractility are ill defined, and has the added advantage of not seriously altering the physiological condition of the muscle.

The results of the length-tension experiments indicate that rabbit taenia coli has static properties similar to skeletal and other smooth muscles (3, 12, 26, 35, 36). Qualitatively, the taenia coli and other muscles have nonlinear passive length-tension characteristics and develop maximum tension when tetanically stimulated at some optimum length.

The dependence of the active tension on muscle length and the existence of an optimum length for tension development suggest that the sliding-filament model (15, 20) proposed for skeletal muscle may be valid for smooth muscle as well. Extrapolation of the active-tension curve to zero tension shows that the taenia coli may be capable of shortening to 20–25% of $l_o$. This is in good agreement with observations of other investigators for guinea pig taenia coli (3, 26), canine trachealis (35), feline duodenum (27), and...
bovine mesenteric artery (23). In contrast, skeletal muscle is capable of shortening to only 50–60% of \( l_o \) due to the presence of the Z discs not found in smooth muscle.

The rabbit taenia coli shows a relatively high degree of passive tension at \( l_o \). Similar results have been reported for guinea pig taenia coli (9) and other smooth muscles (14, 27, 37). The relative positions of the passive and active length-tension curves is dependent upon the amount of connective tissue relative to the contractile material present in the muscle (30, 36). In skeletal muscles, such as the semitendinosus or sartorius, the amount of connective tissue is small and \( l_o \) is less than or equal to the muscle length at which passive tension just appears. Taenia coli, on the other hand, has a high collagen content, 17 mg/g wet wt (A. Jones, personal communication), relative to the actomyosin content, which could account for the passive tension at \( l_o \).

Other investigators have found little or no passive tension at \( l_o \) for taenia coli and other smooth muscles. The immediate consequence would be a shift in the relative positions of the passive and active tension curves (29), which would seriously affect the value of \( P_o \). The discrepancy might be attributed to differences in experimental method. For example, in order to eliminate spontaneous activity other investigators have subjected the preparations to continuous or prolonged soaking in media containing iodoacetic acid (23), epinephrine (3, 26), or epinephrine in combination with procaine (27). Aside from the possible metabolic consequences of prolonged exposure, a combination of these agents is particularly hazardous and has been shown to shift the passive tension curve (26).

The maximum tetanic tension, \( P_o \), developed by taenia coli was less than that of skeletal muscle; 0.89 kg/cm\(^2\) cross section compared to 3.0–3.3 kg/cm\(^2\) cross section, respectively (29). These differences are expected because of the lower actomyosin content of taenia coli (10 mg/g wet wt compared to 70 mg/g wet wt skeletal muscle (28)). The value of \( P_o \) obtained for rabbit taenia coli is within the range of values cited for other smooth muscles: guinea pig taenia coli, 1.5 kg/cm\(^2\) (25), 1.82 kg/cm\(^2\) (3); canine tachealis, 1.1 kg/cm\(^2\) (35); rabbit uterus, 0.13 kg/cm\(^2\) (10); and feline duodenum, 0.42 kg/cm\(^2\) (27), all values based on cross-sectional area. Aside from possible species variations, the differences between the present value and those reported by others for taenia coli are difficult to resolve. It is likely that the failure to account for the passive tension at \( l_o \) would lead to an overestimate of \( P_o \). Furthermore, the various smooth muscles mentioned above were studied at higher temperatures (36–37 C). It is possible that the development of active tension in smooth muscle may exhibit a large temperature dependence. For example, cooling uterine tissue from 40 to 20 C reduced \( P_o \) by nearly 50% (10). Taken in this light, the higher values of \( P_o \) obtained for taenia coli at 36–37 C would be in better agreement with those we obtained at 29 C. A systematic study of the relationship of active tension development to temperature would, of course, better resolve the problem.

Another technical problem which seriously affects interpretation of mechanical responses is the mode of stimulation. Other investigators (12, 26) have used longitudinal field stimulation to obtain tetanic responses from the muscles. Katz and Lou (22) and Sten-Knudsen (34) pointed out that under these conditions, maximal stimulation is not possible, because high field strengths produce irreversible shortening of the ends of the muscle and nonuniform contractions. In addition to the problems cited, in a method of stimulation which relies on conduction, the common use of long muscle strips would only increase the length of an already tortuous conduction pathway (2).

**Force-Velocity Relation**

The cells and myofilaments of contracted taenia coli are essentially parallel and longitudinally oriented (28). Therefore, virtually all of the force generated by the contracting muscle segments is manifested longitudinally. It follows that the load presented to the isotonically contracting taenia coli is along the longitudinal axis of the cells. During the time required to attain maximum velocity, the muscle shortened by less than 5% of its length. The length-tension data show that a length change of 5% would reduce the active tension by less than 5%. Therefore, the active tension developed by the muscle was considered to be constant during shortening, and the length at which the peak velocity was measured was essentially constant.

The inverse relationship between the load or the developed tension and the maximum velocity of shortening could be described by the Hill equation. The similarity of the length-tension and force-velocity relationships of smooth and skeletal muscle suggests that their mechanisms of contraction may be basically the same. Bozler (6) and later Huxley (20) proposed that contraction of smooth muscle occurred by a relative sliding movement between molecules or filaments rather than by changes in their shape. Astbury (4) and Fisher (13) observed no marked change in the wide-angle X-ray diffraction pattern or the strength of the intrinsic component of the birefringence, respectively, when smooth muscle was stretched or allowed to shorten over a wide range of muscle lengths. More recent evidence obtained from biochemical analyses (28) and electron micrographs (31) further support a sliding-filament model for smooth muscle. The actomyosin extracted from smooth and skeletal muscles is similar, and in contracted taenia coli the myofilaments are arranged in parallel.

The primary effects of changing the muscle length from \( l_o \) to the resting length, \( l_m \), were proportional reductions in the maximum-developed tension, \( P_o \), and the maximum velocity of shortening at zero load, \( V_{max} \). This was expressed by equation 3 and the normalized version, equation 6. Either of these two equations is equivalent to:

\[
\frac{V_{max}}{l} = \frac{P_{ol}}{l} \cdot \frac{b}{a}
\]

Because the ratios \( V_{max}/l \) and \( b/a \) are independent of the initial muscle length, it follows that the ratio \( P_{ol}/l \) must also be independent of length. The data show that the ratio \( P_{ol}/l \) is very nearly constant for the two muscle lengths and is in good agreement with this prediction.

It has been suggested that the existence of a large passive tension at \( l_o \) would hinder the determination of the force-velocity characteristics of a muscle (35). This is based on the assumption that large passive tensions would preclude velocity measurements at small loads and that a greater
degree of extrapolation would be necessary to obtain $V_{\text{max}}$. This assumption implies that the force-velocity characteristics are dependent on the total tension. However, the present results clearly show that $V_{\text{max}}$ is not influenced by a relatively large passive tension at $I_o$ because $V_{\text{max}}$ varied with the "active" tension. Hill (19) showed that passive tension of a muscle merely establishes the reference level for active tension; the term $P_0$ in the force-velocity equation is the maximum active tension and not the total tension as implied by these investigators. However, it must be pointed out that the effects of the parallel compliance, responsible for the passive tension, and the series compliance on the force-velocity characteristics of the contractile component have not been accounted for. Therefore, the results obtained in this investigation may apply only for the whole muscle.

For skeletal muscle, the constants $a$ and $b$ are the coefficients of shortening heat and the rate of extra energy liberation during shortening, respectively (18). It has not been directly determined, however, whether these constants bear in this investigation may apply only for the whole muscle.

A comparison of the Hill constants (Table 2) obtained for taenia coli at 22 and 36°C (24) cannot be made with confidence because of the differences in technique. Although the values of $a$ are in good agreement, there is a marked difference in all of the other values. The discrepancies might be traced to a temperature dependence. For example, in skeletal muscle, the constant $b$ is highly temperature sensitive (18). If the same obtains for taenia coli, then the smaller value for $b$ at 22°C can be readily explained. Similarly, $P_0$ is lower at 22°C, and necessarily affects $V_{\text{max}}$. Whereas the term $a/P_0$ is relatively constant for skeletal muscles, this may not hold for smooth muscles. There is great variation among the different muscles which goes beyond the effect of temperature. These variations might be attributed to the different physiological properties of the muscles, but could also be the consequence of the experimental techniques employed.

A striking difference is noted when comparing the maximum velocity of shortening at zero load. Skeletal and cardiac muscles must have the capability of rapid shortening as indicated by the high values of $V_{\text{max}}$. Although there are certain similarities among the various types of muscles, the results indicate that the contractile mechanism in smooth muscles must operate at a slower rate.

Work in this laboratory was supported, in part, by Public Health Service Research Grant HD 03622 from the National Institute of Child Health and Human Development (to M. J. Siegman), and an RCA Predoctoral Fellowship in Physiology (to A. R. Gordon).


Received for publication 26 April 1971.

**Table 2. Comparison of force-velocity constants for various muscles**

<table>
<thead>
<tr>
<th>Constants</th>
<th>Sartorius</th>
<th>Frog (0°C)</th>
<th>Guinea pig (0°C)</th>
<th>Pigeon (0°C)</th>
<th>Rabbit (0°C)</th>
<th>Guinea pig (37°C)</th>
<th>Guinea pig (4°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$, g/cm²</td>
<td>1.29</td>
<td>1.24</td>
<td>0.09</td>
<td>0.03</td>
<td>0.17</td>
<td>0.20</td>
<td>0.033</td>
</tr>
<tr>
<td>$b$, sec⁻¹</td>
<td>0.36</td>
<td>0.10</td>
<td>0.33</td>
<td>0.20</td>
<td>0.17</td>
<td>0.10</td>
<td>0.031</td>
</tr>
<tr>
<td>$P_0$, kg/cm²</td>
<td>0.20</td>
<td>0.04</td>
<td>0.05</td>
<td>0.01</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>$V_{\text{max}}$, sec⁻¹</td>
<td>0.52</td>
<td>0.17</td>
<td>0.33</td>
<td>0.10</td>
<td>0.17</td>
<td>0.20</td>
<td>0.031</td>
</tr>
</tbody>
</table>

REFERENCES


