ABSTRACT

A new technique permits removal of the resting force from the muscle during the course of shortening and study of the maximum velocity of shortening with almost zero load at physiological initial muscle lengths. This unloading has been performed as a sudden unloading to zero total load (zero load clamping), or according to the resting length-tension relations, or according to an arbitrary unloading intermediate between both former modes of unloading. Using these various modes of unloading to zero load during shortening, it has been demonstrated that the maximum velocity of shortening $V_{\text{max}}$ remains constant between maximum length ($l_{\text{max}}$) and a length 12.5% shorter than $l_{\text{max}}$. This unique force (zero load)-velocity ($V_{\text{max}}$)-length (up to 12.5% below $l_{\text{max}}$) relation is independent of the initial muscle length over this range of lengths, independent of the time after the stimulus over the largest portion of the shortening phase, and independent of the sequence of length change and mode of unloading through which it arrived at zero load within this range of lengths.

KEY WORDS: cat papillary muscle force-velocity-length relation myocardium $V_{\text{max}}$ quick release load clamping contractility calcium

In single skeletal muscle fibers, the velocity of shortening of lightly loaded fibers has been shown to be independent of sarcomere length until relatively short sarcomere lengths (i.e., $\leq 1.9\mu$) are reached (1). On the other hand, force development depends greatly on the degree of thick and thin filament overlap and remains constant only between sarcomere lengths of 2.0 to $2.2\mu$ (1). In heart muscle, the problem is somewhat more complex. The muscle length where actively developed tension is maximum ($l_{\text{max}}$) is claimed to be associated with a substantial resting force, and a significant resting force would persist as the initial muscle length is shortened below this length and developed force falls. Moreover, it has been asserted that the maximum velocity of shortening ($V_{\text{max}}$) of the unloaded muscle obtained by extrapolation of the inverse relation between load (force) and velocity is independent of initial muscle length, while developed tension decreases with length (2). More recent studies have shown that $V_{\text{max}}$ is greatly dependent on initial muscle length (3). However, these latter results have been obtained from quick releases which permit only relatively short muscle lengths to be explored (4).

It has been asserted that the contractile state of the heart is related to the level of $V_{\text{max}}$ independent of the degree of myofilament overlap (2, 4). However, this conclusion was based on force-velocity curves derived from isotonic contractions, where considerations of changing time and the hazards of extrapolation to zero load may be raised. Katz (5) has challenged the observations since changes in contractility are thought to depend on the amount of Ca$^{2+}$ delivered to the contractile sites. He has suggested that a variable amount of activated Ca$^{2+}$ would alter force development but not the intrinsic rate of the force-generating process as reflected mechanically by $V_{\text{max}}$. 
In view of the importance of these questions, a new experimental technique has been developed which permits the resting force to be removed from the muscle during the course of contraction. Such an approach permits velocity of shortening to be measured with minimal loads that approach zero and at physiological initial muscle lengths (i.e., lengths between \( l_{\text{max}} \) and 0.85 \( l_{\text{max}} \) where resting force is present). The method permits a study of velocity of shortening relative to muscle length without the problems inherent in a shift of preload, necessary to obtain the initial length, into afterload, which the contractile elements must bear as the muscle shortens. In addition, criteria for suitable papillary muscles are discussed, especially in regard to the smallness of the resting tension relative to developed tension.

**Methods**

Eleven papillary muscles of the right ventricle of cats were used for this study. The muscles were suspended vertically in a bath containing a modified Krebs-Ringer solution (mm): NaCl, 118; KCl, 4.7; MgSO\(_4\), 7H\(_2\)O, 1.2; KH\(_2\)PO\(_4\), 1.1; NaHCO\(_3\), 24; CaCl\(_2\), 6H\(_2\)O, 2.4; glucose, 4.5; pH, 7.38. The solution was bubbled with a 95% O\(_2\)-5% CO\(_2\) gas mixture. The temperature was maintained at 29°C for all experiments. The muscles were stimulated at a rate of 12 pulses/min with rectangular pulses of 5 msec, about 10% above threshold, provided through platinum electrodes arranged longitudinally along both sides of the muscle.

The lower nontendinous end of the muscle was held by a light phosphor bronze muscle clip which was soldered in the middle of the spring of the force transducer. The tendinous end of the muscle was tied with a short silk thread extending upward to the electromagnetic lever system. This system was mounted on a Palmer stand and fixed immediately above the bath. The force transducer system was designed for measuring force from the lower end of the muscle in the bath.

**Electromagnetic Lever System**

The lever was made from magnesium with an equivalent mass of 40 mg and cemented to a coil suspended in a strong field of a permanent magnet. This system had a total compliance of 0.4 \( \mu \)g and a total equivalent moving mass of 225 mg. The current through the coil was controlled by three transistorized current sources. The two main current sources were used for sudden load alterations as described below and were calibrated for step changes in forces of 0.1 g, 1 g, and 10 g up to a total of 29.9 g. The auxiliary third current source was used for slow unloading and generated a given amount of force in order to correct for the resting length-tension relations as described below. Displacement of the lever was measured with a photoelectric system which was linear for a muscle shortening up to 2.2 mm. The velocity of displacement was differentiated electronically with an active differentiator. The relation between the highest frequency component of the input signal of the differentiator to its critical frequency was about 0.02.

**Force Transducer**

The force transducer was also based on an optoelectric system. It comprised a flat brass spring (compliance 6 \( \mu \)g) fitted with a shutter. The spring with shutter was in the bath and a phosphor bronze muscle clip was soldered to the spring. Any movement of the shutter modulated the light from a Ga-As solid-state infrared emitter outside the bath. This light was conducted to the shutter through the solution by means of optical fibers. A second bundle of optical fibers conducted the modulated light to a silicon photodiode mounted next to the lamp outside the solution. The current through the diode was amplified and recorded as indicated below. A third-order Faynter filter for optimal step response was used to eliminate noise. The resonance frequency of the loaded transducer was 450 Hz, and the transient time after filtering was 4 msec.

**Control Units**

In the present experiments both sudden and slow load alterations to zero load were imposed on the shortening muscle. For the sudden alterations, two stimulators (Grass model S4) and the two main current sources with associated electronic circuitry were used to control the system. One of the stimulators provided the stimulus for the muscle and triggered the second stimulator, which provided an output pulse of variable delay and duration. This output pulse switched off the first current source and switched on the second one. In this way, the load imposed on the muscle could be altered between various predetermined values within 3 to 5 msec. The electromagnetic lever system could be damped to various degrees by changing the output voltage of an active differentiator which delivered a feedback signal to the coil.

Slow load alterations (Fig. 1), as used for the length-tension correction, were achieved with an oscilloscope, a cadmium-sulfide light-dependent resistor, two operational amplifiers, and a third current source which drove the electromagnetic lever system.
Maximum Shortening Velocity of Heart

Block diagram of the length-tension correction circuit. I: Electro-magnetic lever system. C, coil; L, lever; P, photoelectric displacement transducer. II: Electronic block diagrams. LDR, light-dependent resistor; OA, operational amplifier; LS, level shifter; CS3, third current source; A, displacement amplifier. The appropriate generated functions are indicated. III: Oscilloscope section. Oscilloscope 1 (memory), with recording of the length-tension curve; oscilloscope 2 (Philips PM 3230), generating the length-tension correction. The shadow mask of the curve is fixed on the screen.

Table 1

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Length (mm)</th>
<th>Cross-sectional area (cm²)</th>
<th>Initial tension (mg)</th>
<th>Total tension (mg)</th>
<th>Resting tension (mg)</th>
<th>Resting (active) tension (mg)</th>
<th>Contralateral (± 5% of max)</th>
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<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
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<tr>
<td>1</td>
<td>6.20</td>
<td>0.85</td>
<td>1.0</td>
<td>4.90</td>
<td>4.90</td>
<td>17.8</td>
<td>12.8</td>
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<tr>
<td>2</td>
<td>8.00</td>
<td>1.00</td>
<td>0.9</td>
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<td>3.80</td>
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<tr>
<td>3</td>
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<td>0.90</td>
<td>0.8</td>
<td>2.70</td>
<td>2.70</td>
<td>14.8</td>
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<tr>
<td>4</td>
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<td>0.7</td>
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<td>1.60</td>
<td>13.4</td>
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<tr>
<td>5</td>
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<td>0.70</td>
<td>0.6</td>
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<td>1.50</td>
<td>12.0</td>
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<tr>
<td>6</td>
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<td>1.30</td>
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<tr>
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<td>0.40</td>
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<td>7.8</td>
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<tr>
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<td>0.2</td>
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<tr>
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<td>0.1</td>
<td>1.00</td>
<td>1.00</td>
<td>5.0</td>
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</tr>
<tr>
<td>Mean</td>
<td>7.68</td>
<td>0.94</td>
<td>0.81</td>
<td>5.08</td>
<td>5.08</td>
<td>10.6</td>
<td>10.6</td>
</tr>
</tbody>
</table>

All values were obtained at initial muscle length 1 L0. See text.

System. The resting length-tension relations were determined in the isometrically contracting muscle. In this way the muscle length could be altered slowly with small step changes between the contractions (Fig. 2, top panel), thus allowing the muscle to adjust to each new length (static length-tension curve). Theoretically, the length-tension relations used for the load correction should be recorded at the same instantaneous velocity as the subsequent velocity of shortening of the muscle during unloading (dynamic length-tension curve). However, a good approximation could be obtained in a semidynamic way, i.e., between two contractions at 1L0, the lever of the electromagnetic system was quickly moved up and down by means of a micrometer, allowing the resting muscle to be shortened and lengthened passively. This procedure was repeated several times at velocities similar to the actual velocity of shortening of the same muscle (semidynamic length-tension curve). Length and tension were recorded respectively on the x and y axes of a memory oscilloscope and replotted on millimeter graph paper. The obtained curve was then cut at the edges and fixed on the screen of a second oscilloscope. Length also formed the x axis for the spot of this second oscilloscope. A light-dependent resistor connected to an operational amplifier and a level shifter was mounted in the center of a light-tight tube which was slid over the ring around the oscilloscope screen. By means of a feedback system, the output of the operational...
FIGURE 2
Effects of unloading of a cat papillary muscle during
shortening (muscle 7, Table 1). Top: Resting and
total force as a function of length of the isometrically
contracting muscle. The muscle was lengthened regu-
larly between the contractions until a length slightly
beyond \( l_{\text{max}} \) was attained, \( l_{\text{max}} \) indicates the muscle
length where active force development (total minus
resting) is maximal. Middle: In the lower part,
velocity of shortening is displayed as a function of
length during shortening of five non-afterloaded iso-
tonic contractions which started shortening from five
different initial muscle lengths (preloads from left to
right: 0.8 g \((l_{\text{rest}})\), 0.6 g, 0.4 g, 0.2 g and 0.1 g).
The preload was subtracted continuously during
the course of shortening by following the resting
length-force relations of the same muscle. Note that
only the shortening phases of the contractions from
the onset of shortening to peak shortening are shown.
Bottom: The force-length (upper) and velocity-length
relations of the five control contractions in which the
preload was maintained constant throughout shorten-
ing were superimposed on the tracings of the middle
panel. The same length scale is used for the three
panels and is indicated both in absolute length values
(mm) and in percent relative to \( l_{\text{mwe}} \) (\( U/l_{\text{mwe}} \)). The
deviations of the curves at length below approximately
8.0 mm must be attributed to nonlinearity of the
displacement transducer.

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The length-force relations were determined in a
semidynamic way as described in Methods. The actual
corrected length-force relation of the muscle was
recorded during shortening in the upper portion of
this panel, using the second spot of the oscilloscope.
Bottom: The force-length (upper) and velocity-length
relations of the five control contractions in which the
preload was maintained constant throughout shorten-
ing were superimposed on the tracings of the middle
panel. The same length scale is used for the three
panels and is indicated both in absolute length values
(mm) and in percent relative to \( l_{\text{max}} \) (\( U/l_{\text{mwe}} \)). The
deviations of the curves at length below approximately
8.0 mm must be attributed to nonlinearity of the
displacement transducer.

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cross-sectional area are given for each individual muscle at the muscle length at which actively developed force was maximal ($l_{\text{max}}$). In our studies, isometrically developed forces at $l_{\text{max}}$ are routinely five to ten times greater than resting forces, with ratios of resting-to-total force below 17-18% (except muscle 4) (mean 15.8 ± 1.9%). In the four muscles in which extracellular calcium was augmented from 2.5 to 5.0 mM, the ratio of resting-to-total force at $l_{\text{max}}$ was smaller than 12%. Papillary muscles that were too short (e.g., less than 5 mm at $l_{\text{max}}$) and subject to mechanical damage or had calculated cross-sectional areas greater than 1.5 mm$^2$ were not used.

**EFFECTS OF UNLOADING ACCORDING TO THE RESTING LENGTH-TENSION RELATIONS**

Figure 2 shows a typical example (muscle 7 in Table 1) of unloading the resting force continuously during shortening according to the resting length-force relation. In the top panel, resting and total force are shown as a function of muscle length. The length at which the actively developed isometric force (total minus resting) is maximal was obtained with a preload (or resting force) of 0.8 g and is indicated as $l_{\text{max}}$. As initial muscle length was shortened and resting force fell, active tension fell progressively. In the middle panel are shown the phase-plane tracings of velocity-length relations of five freeloaded, non-afterloaded isotonic contractions, which started shortening from five different initial muscle lengths. The velocity shown is that from the onset until peak shortening; the velocity during relaxation does not appear. These velocity-length tracings have been superimposed on the same length scale as the length-force relations shown in the top panel. In each of the five contractions, the preload was subtracted continuously during the course of the shortening by following the resting length-force relations of the same muscle. This relation was displayed simultaneously during shortening in the upper part of the same photograph. Note that the velocity of shortening of the unloaded contractions all reached the same plateau of velocity. This plateau was maintained relatively constant (within 5% of peak) until approximately 13% below $l_{\text{max}}$ and then fell with length. The individual and mean values for the length ($1/l_{\text{max}}$) of this plateau obtained in the eleven muscles are shown in the extreme right column of Table 1. The bottom panel of Figure 2 represents the data of the middle panel on which the velocity-length relations of five preloaded isotonic “control” contractions have been superimposed. In each of these control contractions, the preload was maintained constant throughout the shortening phase, as shown on the length-force relation recorded simultaneously during each contraction.

An additional interesting observation was the fact that $V_{\text{max}}$, calculated from the hyperbolic portion (6, 7) of the afterloaded force-peak velocity relations obtained in the
Comparison of the effects of a sudden unloading to zero load (zero load clamping) and of an unloading according to the semidynamic length-force relations (muscle 11, Table 1). Top: Velocity of shortening as a function of length of two isotonic contractions which started shortening from $l_{0\text{max}}$ (close to $l_{\text{max}}$, preload of 0.8 g) and from $l_{00}$ (at a preload of 0.4 g). The load was maintained constant throughout shortening. Middle: Effects of unloading according to the semidynamic length-force relations on the velocity-length relations of isotonic contractions which started to shorten with the same preloads as in the top panel. The tracings were superimposed on the control tracings obtained in the top panel. Bottom: Effects of two zero load clampings at the same preloads superimposed on the tracings of the middle panel. The time from the stimulus to the onset of shortening (latent period) was 20 msec and that to peak isometric tension, 290 msec. See text.
length and tension changes through which it arrived at that length and load. Therefore studies undertaken in which the unloading was performed in an arbitrary way. In Figure 4 (muscle 11 in Table 1), the effects of unloading the muscle from two initial lengths by following the semidynamic resting length-force curve (middle panel) are compared with the effects of an abrupt unloading to zero total load from the same two preloads (bottom panel). These “zero load clampings” were imposed immediately following the latent period from the stimulus to the onset of shortening (i.e., after 20 msec) and were maintained for 50 msec. Then the original preload was restored. It is clearly shown in the bottom panel that after a short acceleration transient during the sudden unloading the same maximum velocity of shortening and plateau were attained.

It appears that over a range of lengths of 12.5% below $l_{max}$ (up to 5.25 mm in the present muscle; see also Table 1) maximum velocity of shortening at zero load is constant (±5% of its maximum value) and is not determined by the sequence of length change and mode of unloading through which it arrived at zero load and at this range of lengths encompassed. Moreover, as shown in previous studies (6, 8) for the force-velocity-length relations at any given total load, the present unique force (zero)-velocity ($V_{max}$)-length (12.5% $l_{max}$) relation is also independent of time. For example, in Figure 4, the same plateau of maximum velocity of shortening at a length of 5.5 mm is reached by the four contractions, despite a difference in time of 55 msec at 0.8 g and of 30 msec at 0.4 g preload. Thus at the preload of 0.8 g this length of 5.5 mm is attained at 95 msec after the stimulus by the progressively unloaded contraction and at only 40 msec by the zero clamped or rapidly unloaded contraction. With a preload of 0.4 g, the length of 5.5 mm is reached after 70 msec with slow unloading and at 40 msec with rapid unloading.

Following a brief deceleration transient at the end of the zero load clamping period (Fig. 4, bottom panel), the original control curves, in which the preload had been maintained throughout shortening, were again reached. However, the “clamped” contractions shortened somewhat further than their controls. This can be explained by the fact that peak shortening was attained earlier in the clamped contractions because of the higher velocity of shortening for a finite time interval during the clamping period. As demonstrated in earlier studies (6, 8), time may indeed become an important factor near peak shortening when active state is declining. However, this is certainly not the case over the major portion of the shortening phase.

Of further interest is the fact that the $V_{max}$ values calculated from the hyperbolic portion of the afterloaded force-peak velocity curves in the same muscle (17.0 mm/sec at the highest preload and 18.3 mm/sec at the lowest one) again closely resemble the measured $V_{max}$ during both modes of unloading.

In Figure 5 the same experiment shown in Figure 4 was repeated at only one preload of 0.8 g. Similarly superimposed are the control contraction 1, the slowly unloaded contraction 2, and the zero load clamped (or rapidly unloaded) contraction 4. The velocity-length relations indicated as 3 are from a contraction in which an arbitrary unloading to zero load was performed according to a resting length-tension curve intermediate between the true length-tension relation of this muscle and the length-tension relation of the zero clamping. The same conclusions can be formulated as for Figure 4.

**INFLUENCE OF INCREASED CALCIUM CONCENTRATION**

Figure 6 shows the effects of an augmented calcium concentration on the force-length relations (top and middle panels) and on the velocity-length relations of an isotonic contraction in which the preload of 0.7 g ($l_{max}$) was maintained throughout shortening (lower two curves of bottom panel) and in which this preload was subtracted according to the resting length-tension curve (upper two curves of bottom panel). During unloading, a plateau of maximum velocity for unloaded...
Comparison of the effects of an unloading according to the semidynamic length-force relations (contraction 2), to a zero load clamping (contraction 4) and to an arbitrary length-force relation (contraction 3). Contraction 1 is the control contraction in which the preload of 0.8 g was maintained constant throughout shortening. The tracings were redrawn in the insert for clarity (the course of the zero load clamping is indicated by the dotted lines).

Influence of an increased calcium concentration. Top: Resting and total force-length relations in the presence of 2.5 mM Ca\(^{2+}\). Middle: with 5.0 mM Ca\(^{2+}\). Bottom: Velocity-length relations (at 2.5 and at 5.0 mM Ca\(^{2+}\)) of two isotonic contractions in which the preload of 0.7 g (l\(_{max}\)) was maintained constant throughout shortening (lower two curves) and in which this preload was subtracted according to the resting length-force relations (upper two curves).

In Figure 7 the length-tension relations of four isometric contractions, which were rapidly released from peak force to zero afterload, shortening was maintained over the same range of lengths at both calcium concentrations. Moreover, when the contractility was augmented, measured V\(_{max}\) clearly increased. The V\(_{max}\) values calculated from the afterloaded force-peak velocity curves were 23.5 mm/sec at 2.5 mM Ca\(^{2+}\) and 31.7 mm/sec at 5.0 mM Ca\(^{2+}\). These calculated values for V\(_{max}\) are again virtually identical to those obtained with unloaded shortening. In four muscles, mean calculated and measured values of V\(_{max}\) of 20.06 ± 1.54 and 21.34 ± 1.87 mm/sec were found at 2.5 mM Ca\(^{2+}\) and of 29.18 ± 4.10 and 28.58 ± 3.19 mm/sec at 5.0 mM Ca\(^{2+}\).
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FIGURE 7

Influence of a quick release on the force-length relations (muscle 8, Table 1). Top: Resting and total force-length relations. Bottom: At four different lengths (preloads from left to right: 1.4 g, 1.0 g, 0.6 g and 0.2 g), an isometric contraction was recorded up to peak force and then suddenly (within 5 msec) released to the preload. The resting length-force (up to 5.5 g) relations were superimposed on the same diagram. The shortening of the muscle occurring during the releases is 0.55 mm (6.1%) at 1.4 g, 0.6 mm (6.8%) at 1.0 g, 0.7 mm (8.2%) at 0.6 g and 0.8 mm (9.8%) at 0.2 g.

The shortening of the muscle during the fall in force corresponded to the previous extension of the SE and hence shortening of the CE. In Figure 7 the shortening of the CE at peak force was 6.1% from the initial muscle length at a preload of 1.4 g, 6.8% at 1.0 g, 8.2% at 0.6 g and 9.8% at 0.2 g. Following the quick release, transients on the velocity tracing are unavoidable, so an additional 3–5% shortening of the CE must be taken into account. This yields lengths which are 9–15% shorter than \( l_{\text{max}} \) before any reasonable velocity measurement can be made, when quick release methods are used for the study of force-velocity relations in heart muscle. From the present study it is apparent that maximum velocity of shortening \( (V_{\text{max}}) \) clearly starts to fall at these shorter lengths, where resting force approaches zero. This fact would become even more apparent if still shorter initial muscle lengths (up to \( l_{\text{min}} \)) had been used. As explained in the discussion, this shortening of 6.1–9.8% of the CE of heart muscle during force development may largely explain the marked dissociation between \( V_{\text{max}} \) and \( P_0 \) of the “total” heart muscle over the plateau range of \( V_{\text{max}} \).

Discussion

In the present study a new technique has been described which permits the resting force (preload) to be removed from the muscle during the course of isotonic shortening. This approach permits measurement of velocities of shortening of papillary muscles contracting with minimal loads, starting from relatively long initial muscle lengths with high resting forces and shortening over a wide range of lengths.

Since it has been generally recognized (9–12) that no one analog model can explain all known experimental data in heart muscle, the initial intent of the present experiments was to consider this correction for resting length-tension as a means of unloading the muscle at physiological lengths rather than in
terms of any of the proposed models. Therefore, the more general term of "unloaded shortening" rather than "CE clamping" has been used. Furthermore, in a recent study (8) it was clearly demonstrated that heart muscle always senses "total" load and that at any given length the velocity of shortening always adjusts to this instantaneous total load, independent of the sequence of length and tension changes through which it arrived at that length and load. This fact has also been confirmed in the present study by the use of arbitrary unloadings which were different from the actual static, dynamic, or semidynamic resting length-tension curves of the same muscle. It appears that the maximum velocity of shortening at zero load is the same regardless of the preceding mode of unloading. Hence, maximum velocity of shortening is determined only by the total load, even if it is zero load, and not by the sequence of length changes or the mode of unloading through which it arrived at zero load, at least within this range of lengths. From the present findings and from our recent study (8) it becomes clear that any considerations of analog models and especially the role and origin of the resting tension will have to be reconsidered for heart muscle relative to these findings. In this regard, attention must be called to various recent studies in which it has been reported that both in skeletal and cardiac muscle a large portion of the resting tension appears to be generated by a weak bonding between the contractile filaments, rather than by supporting structures in the fibers (13–20).

In the present study, using these different techniques of unloading to zero load, it has been demonstrated that the maximum velocity of shortening of unloaded contractions remains constant to within 5% of peak between \( l_{\text{max}} \) and a length 12.5% shorter than \( l_{\text{max}} \) and is quite independent of the initial muscle length and also of the time after the stimulus over the largest portion of the shortening phase.

Utilizing single fibers of skeletal muscle, Gordon et al. (1) demonstrated that velocity of shortening with very light loads is independent of sarcomere length and myofilament overlap over a wide range. Velocity of shortening remained constant with sarcomere lengths ranging from 3.0 \( \mu \) down to 1.85–1.9\( \mu \), but fell markedly as sarcomere lengths of 1.6–1.7\( \mu \) were approached. In contrast, force development was greatly dependent on sarcomere length except over a relatively narrow range of sarcomere lengths between 2.2 and 2.0\( \mu \). These results are directly comparable to the results of the present study, although very long sarcomere lengths (>2.3\( \mu \)) in heart muscle cannot be studied because of its high resting stiffness. In previous studies with isolated papillary muscles, diastolic sarcomere lengths at \( l_{\text{max}} \) have been shown to measure 2.2\( \mu \) (21–23).

In the present study, maximum velocity of shortening (\( V_{\text{max}} \)) with minimal loads remains constant between \( l_{\text{max}} \) and a muscle length 12.5% less than \( l_{\text{max}} \). This would comprise sarcomere lengths between 2.2 and about 1.9\( \mu \). Over this range of sarcomere lengths, the overlap of thick and thin myofilaments would be optimal, and the present findings of a constancy of \( V_{\text{max}} \) over this range is consonant with results obtained with single skeletal muscle fibers. Moreover, in the intact ventricle in diastole, midwall sarcomere length averages 2.07\( \mu \) with a range between hearts of 2.05–2.15\( \mu \). With systole, sarcomere lengths decrease to between 1.85 and 1.95\( \mu \) (24). Indeed, in the resting heart, diastolic sarcomere length is never shorter than 1.9\( \mu \) even if the ventricle is completely emptied (25). Thus the range of sarcomere lengths in isolated muscle, where \( V_{\text{max}} \) is constant relative to length, encompasses the range of diastolic sarcomere lengths found within physiological ranges in the intact ventricle.

When sarcomere lengths of 1.8\( \mu \) or less are reached during the course of shortening, \( V_{\text{max}} \) falls with length. The reason for this fall in \( V_{\text{max}} \) at these shorter lengths is poorly understood. At these short sarcomere lengths, thin filaments pass into the opposite half of the sarcomere, and interference with force-generating bonds has been suggested (1). In
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this range of short sarcomere lengths, restoring forces become evident and may contribute to a parallel fall in force and \( V_{\text{max}} \). Furthermore, whereas sarcomere lengths in the resting muscle were found to be directly related to muscle length at lengths greater than 85\% of \( l_{\text{max}} \), no such relationship exists below this point due to curling of the myofibrils (23) or to other microscopically visible distortions (26, 27).

The question remains as to why force should be altered between \( l_{\text{min}} \) and \( l_{\text{u}},,,,j \) minus 12.5\% if myofilament overlap is optimal. Previous studies (4, 6) have shown that a major reason for the fall in measured isometric force of the muscle is the contractile element (CE) shortening at the expense of the series elastic element (SE), moving the CE down the length-tension curve. Indeed, one might predict that CE isometric force and \( V_{\text{max}} \) are both independent of initial muscle length over the range of physiological initial muscle lengths from \( l_{\text{max}} \) down to 0.87 \( l_{\text{max}} \). The dissociation between \( V_{\text{max}} \) and \( P_0 \) for the total muscle may derive largely from the high compliance of the SE in heart muscle (6, 20), as can be predicted from the quick-release experiments shown in Figure 7.

Of further interest is that, when the contractility is augmented by the extracellular calcium, the plateau of unloaded velocity and the force of contraction are both increased. This provides new direct experimental evidence that the previously demonstrated augmentation of the calculated \( V_{\text{max}} \) when the calcium concentration increases is indeed a true characteristic of heart muscle due to an increased rate of energy turnover at the level of each crossbridge between actin and myosin filaments. Furthermore, the explanations for a rise in \( V_{\text{max}} \) which are based on an increase in the number of force generators in the presence of a viscosity cannot be supported if one views the studies on heat measurement in heart muscle (28). In the presence of increased calcium, Gibbs shows that the heat for a given amount of tension is not augmented. If a large amount of viscosity had to be overcome to increase velocity of shortening, a great amount of excess heat would be produced. Clearly, from these considerations and from the present study, it appears that \( V_{\text{max}} \) does actually rise. Moreover, increasing extracellular calcium produced an augmentation of \( V_{\text{max}} \) without changing the range of the plateau over which \( V_{\text{max}} \) was independent of length, supporting the view that the latter was dependent on the myofilament overlap. This latter fact also implies the constancy of \( V_{\text{max}} \) over the physiological range of myofilament overlap between 2.2 and 1.85\mu. The implications of the present results on the extrapolations of myocardial velocity measurements from quick release methods (3, 29, 30), have now also become evident. It is clear that following a quick release from physiological initial muscle lengths, any reasonable velocity measurement can be made only at lengths 9 to 15\% below \( l_{\text{max}} \), where maximum velocity of shortening clearly starts to fall. In addition, most quick releases are performed rather late in the course of the contraction (3, 30), i.e., about two-thirds of the time from stimulus to peak tension. After this time, active state may start to decline (4, 6, 8) and the force-velocity relation, and hence \( V_{\text{max}} \), may also become time-dependent. This is certainly not the case in the first portion of the contraction, from onset to near peak shortening (8). Moreover, the quick release itself may also alter the subsequent course of the active state (6, 12), and hence influence the velocity measurement and the calculation of \( V_{\text{max}} \). Thus the length dependence in the shorter length range, as demonstrated in the present study, and the influence of the time course of the active state and the uncoupling action of a quick release largely help to explain the discrepancies in recent literature. Another reason for these discrepancies is the lack of standards of performance of healthy papillary muscles of the cat (20). In our experience, developed force should exceed resting force by 5 or 6 to 1 in adequately functioning preparations. Smaller ratios of developed force to resting force usually reflect mechanical damage to the preparation, of whatever etiology. Very short (<5 mm at
l_{\text{max}}) or very thick (> 1.5 mm²) cat papillary muscles may function poorly. One should also be most careful with the interpretation of the results with papillary muscles obtained from other species such as the rabbit or rat, which in general develop less force and appear to be relatively stiffer.

From the present study, it appears that the velocity-length-load relation of an isotonic contraction at any given total load (8) is also found at zero total load. Furthermore, this relation is not only independent of the initial muscle length but also of the time over the largest portion of the shortening phase, and of the preceding sequence of length change and mode of unloading. The fact that the length of the unloaded velocity-length plateau does not change with increased calcium argues strongly for the fact that this plateau depends on the relative myofilament overlap.

Acknowledgment
The authors wish to recognize the excellent assistance of Jacqueline Van de Putte and Willy Delnat.

References
25. Spotnitz, H.M., Sonnenblick, E.H., and Spiro,
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Circ Res. 1971;29:63-75
doi: 10.1161/01.RES.29.1.63

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the
World Wide Web at:
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