SLControl: PC-based data acquisition and analysis for muscle mechanics

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Campbell, Kenneth S., and Richard L. Moss. SLControl: PC-based data acquisition and analysis for muscle mechanics. Am J Physiol Heart Circ Physiol 285: H2857–H2864, 2003. First published August 7, 2003; 10.1152/ajpheart.00295.2003.—SLControl is a computerized data acquisition and analysis system that was developed in our laboratory to help perform mechanical experiments using striated muscle preparations. It consists of a computer program (Windows 2000 or later) and a commercially available data acquisition board (16-bit resolution, DAF5216a, Microstar Laboratories, Bellevue, WA). Signals from the user's existing equipment representing force, fiber length (FL), and (if desired) sarcomere length (SL) are connected to the system through standard Bayonet Neill Concelman cables and saved to data files for later analysis. Output signals from the board control FL and trigger additional equipment, e.g., flash lamps. Windows dialogs drive several different experimental protocols, including slack tests and rate of tension recovery measurements. Precise measurements of muscle stiffness and force velocity/power characteristics can also be accomplished using SL and tension control, respectively. In these situations, the FL command signal is updated in real time (at rates ≥2.5 kHz) in response to changes in the measured SL or force signals. Data files can be exported as raw text or analyzed within SLControl with the use of built-in tools for cursor analysis, digital filtering, curve fitting, etc. The software is available for free download at http://www.slcontrol.com.

MUCH OF OUR KNOWLEDGE about the mechanical properties of biological systems has come from measurements performed using striated muscle preparations. Most early experiments using these tissues (5), and references therein, focused on quantifying their basic mechanical properties (shortening velocity, power output, etc.). More recent work (8) often targets specific molecular mechanisms, e.g., the role of protein kinase phosphorylation in contracting myocardium. Irrespective of the underlying aim, however, mechanical experiments using striated muscles require control and measurement of macroscopic variables, such as muscle length, stiffness, and tension.

Many ingenious protocols have been developed over the years but most mechanics experiments can be categorized as belonging to one of two distinct groups. The first group consists of experiments in which the force generated by the muscle is measured while the length of the preparation is carefully controlled. Experiments in this broad category vary from relatively simple assays of isometric tension, i.e., developed tension at fixed muscle length (6), to complicated measurements of viscoelastic properties during repeated length changes (1). The second group represents the converse type of experiment during which the length of the preparation is measured while the tension is controlled. Most experiments of this type correspond to measurements of loaded shortening, e.g., Ref. 7, but other paradigms [such as measuring the increase in muscle length in response to a slowly increasing force (2)] are possible, of course.

In the early days of muscle mechanics, these different types of experiment often required distinct pieces of apparatus. Measurements using controlled length changes incorporated elaborate systems based on motor-driven kymographs (5, p. 9); those using controlled tensions involved muscles pulling on appropriately loaded levers. Careful design minimizes the inertia of moving parts in this type of equipment, but experiments based on this technology are really only practical with whole muscles. Today's experiments often use much smaller preparations, e.g., single cardiac myocytes, which develop such tiny forces (often much less than 1 μN in measurements of passive properties) that traditional experimental apparatus is impractical.

Two alternative approaches have been developed to overcome this difficulty. The first (and more common) technique is to attach one end of the muscle to a force transducer, which measures the tension in the preparation. The other end of the muscle is attached to an actuator, which can be used to change the preparation's length. This design is obviously best suited to experiments in the broad length control category. The second technique, ideal for tension control experiments, is to fix one end of the muscle to an immovable object and attach the other end to a lever (such as the pointer of a moving iron ammeter), which pulls with a predetermined force.

It is, of course, possible to use either arrangement for length or tension control experiments by incorporating appropriate feedback. In the first arrangement, constant tension can be maintained under a variety of

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different experimental conditions by carefully adjusting the overall muscle length in response to minute deviations in measured force. Preparation length can be maintained in the second arrangement by appropriate adjustments in muscle tension.

Again, two broad techniques have been used to implement this type of servo control. In the first, negative feedback is applied via analog circuitry. This approach allows rapid system response with appropriately designed equipment and has been used to impose step tension changes in as little as 150 μs (9). Elaborate diode networks (4) allow control to be switched between different inputs (force, length, etc.) without compromising system performance. Analog circuitry is capable of unsurpassed frequency response and remains the method of choice in mechanical experiments requiring extremely rapid control. The disadvantage of the method is that the circuitry is generally difficult to design, construct, and tune for optimal performance.

The alternative approach is to impose feedback using a computerized control system. In this type of scheme, the experimental apparatus may be regarded as a subcomponent of the overall system (Fig. 1). Signals, such as muscle force and length, are passed from the experimental apparatus to the control system, thus providing information about the preparation’s macroscopic state. In turn, the control system passes signals (e.g., motor commands), which can alter the state of the experimental apparatus. Real-time control is possible if the command signals can be rapidly updated in response to changes in the output signals from the apparatus. This sort of task places severe constraints on the type of computer system that can be used. Stable control requires that command updates are issued at regular time intervals. If a rapid system response is also required, the time interval between a change in the state of the muscle being measured and a corrective command being issued must be very short as well. These requirements are beyond the capability of conventional multitasking operating systems (e.g., Windows, Mac OSX; however, see Ref. 3), which by their very definition share processor time between different applications. Suitable performance can, however, be achieved either by computers running real-time operating systems (such as RTLinux) or by transferring the time-critical tasks to dedicated hardware.

SLControl is a computer system developed in our laboratory to help perform muscle mechanics experiments, uses the second strategy. The package consists of a computer program running in a Windows environment (Windows 2000 or later) and a commercially available data-acquisition processor (DAP, model 5216a, Microstar Laboratories; Bellevue, WA) installed in a PCI slot in the host personal computer (PC). The DAP incorporates a 400 MHz AMD K6 III+ processor chip, which allows the board to handle all time-critical tasks (including data acquisition, command output, and calculations inherent to feedback control) without requiring intervention from the host PC.

The resulting system has numerous advantages. First, it is relatively inexpensive and easy to install. All that is required (in addition to the force transducer, actuator, etc., which are assumed integral to the existing apparatus) are a PC (with installed software) and a DAP board (the 5216a DAP costs around $4,000). Second, the system should be compatible with a wide range of commercial and custom-built instrumentation. SLControl assumes only that the experimental apparatus 1) provides analog signals proportional to muscle length and force and 2) incorporates some type of actuator, which varies muscle length and which is controlled by an analog signal. Third, SLControl is capable of stable real-time control at command update rates >2.5 kHz, sufficient for all but the most demanding applications. Moreover, control can be switched at will between different signals [force, sarcomere length (SL), etc.] in the time interval between consecutively sampled points. Fourth, the control software is extremely flexible. Windows dialogs are provided for several different experimental protocols, e.g., slack tests, rate of tension recovery measurements, force velocity/power assessment, etc. Other protocols can be developed with minimal effort.

**IMPLEMENTATION**

**Overview.** SLControl achieves real-time performance in a Windows environment by delegating time-critical tasks to a separate processor running on a DAP installed in the host PC (Fig. 1). The DAP itself is...
controlled by commands written in Microstar Laboratories’s proprietary scripting language DAPL 2000. SL-Control’s experimental protocols generate code in this format automatically and pass it to the DAP using Microstar’s Accel 32 server software. The DAP then interprets the command sequence and initiates an experimental recording. Annotated examples of sample DAPL code are available at http://www.slcontrol.com. Once the experiment is complete, a signal is passed back to the user interface, which reads the acquired data from the DAP, saves it to disk in ASCII format, and displays the full record in an appropriate dialog (see Fig. 2).

An advantage of this approach is that the complexity of the underlying control scheme is hidden from the user, who interacts with the system solely through standard Windows dialogs. It is not strictly necessary for the end user to understand the intricacies of the DAPL control scheme to extract maximum system performance.

The user interface was developed in Microsoft Visual C++ version 6.0 and is a standard Microsoft Foundation Class dialog-based application. It runs in both Windows 2000 and Windows XP environments and has modest minimum system requirements. Satisfactory performance is easily attained on a 1 GHz Intel processor running Windows 2000 with 256 MB RAM. Full installation (including example data files) requires ~25 MB of free hard disk space. The program itself is ~1 MB in size.

Examples of DAPL algorithms used for SL and tension control experiments are discussed fully below.

Experimental apparatus. As described above, SL-Control should be compatible with a wide range of instrumentation. We have used the software with several different commercial and custom-built force trans-
ducers and actuators. Most of the initial development was, however, performed using experimental apparatus incorporating a motor and a force transducer supplied by Aurora Scientific (Ontario, Canada). Recordings made with this equipment are presented in this work to illustrate some of the capabilities of SLControl and the apparatus is described here accordingly.

Schematic diagrams of the equipment are presented in Fig. 1 of this work and in more detail in Fig. 1A of Campbell and Moss (1). Briefly, single muscle fibers (length ~1 mm, diameter ~80 μm) are connected between a motor (model 312B, time for 100 μm step ~0.8 ms, Aurora Scientific) and a force transducer (model 403, resonant frequency ~600 Hz, Aurora). A laser beam (HeNe, 10 mW, Melles Griot; Irvine, CA) is then projected through the muscle and one of the first-order diffraction lines is imaged onto a lateral effects photodiode detector (model 1239 diode, UDT Instruments; Baltimore, MD). A differential amplifier (model 301-DIV, bandwidth 5 kHz, UDT Instruments) produces an output voltage proportional to the position of the centroid of light incident on the detector and thus provides a direct measure of the mean SL in the center of the preparation.

Analog signals representing force, SL, and muscle fiber length (FL) (equivalent to reported motor position) are connected to the S0, S1, and S2 analog inputs, respectively, of a 5216a DAP (Microstar Laboratories) via an MSTB009 termination board (Microstar). The A0 analog output from the DAP triggers a digital oscilloscope (which was used to verify accurate signal acquisition during development testing), whereas the A1 channel is connected to the input of the motor controller. In most of our experiments to date, the S3 DAP input has been used to record the intensity of the light incident on the photodiode detector but this is not strictly essential for adequate servocontrol. The S3 channel (and indeed any of the other 12 analog input channels available on the DAP) could instead be used to record additional signals (e.g., fluorescent polarization intensities) of use in different types of experiment.

Calibration. Before SLControl can be used to perform mechanical experiments, it must be provided with basic information about the experimental apparatus. Specifically, the user must supply numerical values for four different parameters: FLPOLARITY, FLCOMMAND, FLRESPONSE, and FORCERESPONSE.

The first of the parameters, FLPOLARITY, defines whether the muscle lengthens or shortens when the actuator command signal (the A1 DAP output) increases. A value of +1 indicates that the muscle length increases with increasing command voltage; a value of −1 that muscle length decreases. No other values should be used.

FLCOMMAND and FLRESPONSE (both expressed in units of μm/V) define the behavior of the length actuator. FLCOMMAND is the magnitude of the actuator movement when the command signal changes by 1 V. FLRESPONSE is accordingly defined as the actuator movement when the position output signal (normally connected to the S2 DAP input) changes by 1 V. The actuator command and response signals are assumed to be of equal polarity, i.e., if the command signal increases, so does the response signal. If this is not the case, the FLRESPONSE calibration factor should be multiplied by −1.

The final calibration factor, FORCERESPONSE, defines the behavior of the force transducer incorporated in the apparatus. It is expressed in units of N/V and represents the increase in measured force (in N) when the output voltage (normally connected to the S0 DAP input) increases by 1 V. Again, if the output voltage actually decreases in response to increased loads, the calibration factor should be expressed as a negative value.

Values for these parameters are stored in an ASCII text file located in SLControl’s parent directory. The user can thus adjust the parameter values for different experimental setups simply by editing the file. When the program is started, SLControl scans the calibration file and extracts the appropriate values to global variables defined in the interface source code. These values are subsequently used to control all experimental measurements and are also written to disk with each acquired record. This simple approach ensures that if a data file is opened on a different system at some later time, the appropriate calibration factors are available for complete analysis of the original record.

A brief tutorial explaining how to measure these calibration parameters and how to update the appropriate calibration file is available at http://www.slcontrol.com.

Algorithms/performance. Although many laboratories have developed computerized data-acquisition systems, a limiting feature of most of the devices used in muscle physiology experiments is that they can only be used to control protocols in which the muscle preparation is subjected to a predefined length change. This constraint arises because the timing delays inherent to conventional operating systems prevent the host computer from rapidly updating the motor command voltage in response to changes in the measured feedback signal.

SLControl overcomes this difficulty by delegating all of the time-critical tasks to a separate processor running on the DAP board installed in the host PC. This architecture ensures that the system can perform experiments with the use of conventional FL control or alternatively (with appropriate feedback) under SL or tension control.

SL control. Precise measurements of the mechanical properties of contracting muscle fibers are often compromised by series compliance artifacts. Small regions of the muscle (normally near the attachments) elongate disproportionately during imposed movements so that different parts of the preparation are subjected to different relative changes in length. Under these conditions, calculated stiffness values primarily reflect the properties of the muscle attachments rather than of the homogeneous central portion of the fiber.

SLControl helps to minimize this sort of artifact because it allows experiments to be performed under
sarcopemre length control, hence the name. In this approach, the actuator controlling muscle length is driven not by a predetermined command waveform but rather by a feedback signal derived from an optical measurement of the mean SL of the preparation. The contracting core of the fiber is thus subjected to a well-defined length change irrespective of end-compliance effects. Potential artifacts are eliminated, and mechanical measurements can be made with greater precision.

In our experiments to date, SL has been determined with the use of a laser diffraction technique (Fig. 1). However, SLControl itself makes no specific assumptions about this and other techniques (e.g., line-scan analysis of direct sarcopemre imaging) could easily be used instead. All that is required for accurate control is that a real-time analog signal proportional to the mean SL of the preparation is passed to the DAP.

The first step in performing an experiment under SL control is to calibrate the SL signal. Our software performs this procedure automatically by measuring the changes in the SL signal, which result from small (~1% muscle length) movements of the actuator. Simple calculations then yield a calibration factor, which defines the expected change in SL signal (in analog-to-digital conversion units) for a given change (in μm) of muscle length.

This calibration factor in turn allows the expected values of the SL signal (assuming negligible end compliance) to be precalculated for every point in a length control protocol. These values are passed to the DAP before a recording is initiated and stored in a DAP pipe (a structure which is roughly analogous to an array in a conventional programming language) named ptarget (Fig. 3). Also passed to the DAP (stored as plast_out) are corresponding values of the actuator command signal, i.e., the signal, which will be passed to the actuator if SL control is not imposed. Finally, pservo is filled with individual values indicating whether SL control will be active (pservo = 1) or inactive (pservo = 0) for the corresponding acquisition period.

Once all of the necessary data have been received, the DAP initiates the experimental recording. Data acquisition and signal output tasks are controlled by specialized input-output routines (example code is available at http://www.slcontrol.com). The actual values of the actuator command voltage are calculated using the procedure illustrated in Fig. 3. For each acquired point, the DAP notes whether SL control is active or not (i.e., whether pservo is 1 or 0) and sets plast_out to pfeedback or plast_out accordingly. plast_out was predefined by the experimental protocol. pfeedback is calculated in real-time using the current values of ip1 (the measured SL signal) and plast_out (the last command value passed to the actuator) and the user-defined variable gain. The value stored in plast_out is then passed to op1 (the output to the actuator) and to plast_out (in preparation for the next cycle).

It should be obvious that our control algorithm uses only proportional feedback control, i.e., when SL control is active (pservo = 1) the actuator position is adjusted by an amount proportional to the difference between the measured and the desired SL signal. This is in contrast to most analog control circuits, which normally invoke additional correction terms, which vary with the integral and the derivative of the difference between the measured and the desired signals. We investigated the addition of such terms to our control algorithm during the initial development

```
fill plast_out 0
fill pservo 0 0 0 0 1 1 0 0 0
fill pfl 1 2 3 4 5 6 7 8 9 10
fill ptarget 2 4 6 8 10 12 14 16 18 20
pdef control:
pout=((ip1-ptarget)-(gain*(ip1-pttarget)))+(pservo*pfeedback)
copy(pout,plast_out,pl)!
merge(ip0,ip1,ip2,ip3,ip4,pl)
end
```

![Flowchart](image)

Fig. 3. A simplified version of the SL control algorithm as implemented in the DAP language (DAPL) scripting format. The control procedure, delineated by the pdef and end commands, executes each time new data points are acquired. Variable names beginning with "p" represent DAP pipes. Calculations invoking these structures use the next available element on each iteration. The parameter gain is a conventional single-valued variable set by the user in the interface dialog. A single value of plast_out is required to initiate the algorithm. The flowchart summarizes data flow in the control loop. In this example, the actuator command voltage would be updated 10 times (set by the number of points defined in the appropriate fill commands). Points 1–4 and 8–10 would be updated under fiber length (FL; actuator position) control. Points 5–7 would be determined by SL control, i.e., the actuator command voltage would be adjusted in such a way as to minimize the difference between the current SL signal (ip1) and the desired value ptarget, precalculated in this example with an arbitrary SL/FL calibration factor of 2. The final merge command passes data back to the host personal computer (PC). The actual algorithm employed by SLControl has an additional feature, which for simplicity is not shown here. It stores the last value of the SL signal (ip1) recorded before servocontrol is employed, thus allowing movements to be imposed relative to the prevailing SL rather than to some arbitrary voltage level. An annotated version of the full-length control algorithm is available at http://www.slcontrol.com.
stages of SLControl but found that they did not substantially improve system performance.

In part this may be because of the limited frequency response of our length actuator (time for 100 μm step ~0.8 ms). However, it should also be noted that in a digital control system like SLControl, integral, and derivative correction terms can only be calculated from a series of acquired points. They thus change only when new data points are acquired. In our experiments, the maximum sustainable update rate is 2.5 kHz under length control and our initial tests showed that the integral and derivative terms did not accumulate quickly enough under these conditions to make a substantial contribution to the system’s step response. This is obviously a very different situation from that found in analog circuitry where the control signal is subject to continual adjustment.

New users should be aware that the calibration procedure described above for the SL signal is only accurate when there is negligible compliance in the muscle attachments during the test length changes. If this is not the case, the SL calibration factor will be invalid and inappropriate values will be passed to the ptarget data structure. We guard against this possibility in our own experiments by 1) calibrating the SL signal under conditions where the muscle preparation is in a relaxed state, i.e., series compliance is likely to be negligible; 2) ensuring that calibration values deduced from different sized actuator movements are consistent; and 3) checking that recordings made with and without SL control under relaxed conditions result in similarly sized actuator movements.

Another point worth emphasizing is that users should not attempt to impose experiments under SL control until they are confident that their feedback signal is a reliable indicator of the mean SL of their preparation. Our experience with laser diffraction techniques suggests that regional heterogeneity in the striation patterns of some types of preparation can result in a relatively broad, diffuse, and diffracted beam. (This is often a particular problem in contracting myocardial preparations.) Under these conditions, the apparent movement of the diffracted beam is often less than that expected from the overall change in preparation length and the mean SL of the preparation cannot be reliably determined (2). Attempts to impose closed loop SL control under these conditions are unlikely to yield satisfactory results.

One factor that seems to be important for maintaining stable striation patterns during prolonged activations is the amount of series compliance associated with the attachments between the muscle preparation and the experimental apparatus. A variety of techniques (including metal foil “t-clips” and biologically inert adhesives) have been used in different laboratories, but we invariably favor the combination “crimp” and “glutaraldehyde fixation” technique depicted schematically in Fig. 1B of Ref. 1. The development of this technique enabled us to perform extensive measurements on rat soleus fibers during which the preparations could be subjected to ~500 consecutive stretches under SL control without noticeable changes in their appearance or mechanical properties (1).

Example recordings performed under FL and SL control in a contracting cardiac preparation are illustrated in Fig. 4. Close inspection shows that SL control emphasizes the initial phase of the tension response to each lengthening movement but does not change the qualitative features of the muscle’s response. The technique should therefore be regarded as a refinement of the more conventional FL control protocol and is of most use in quantitative measurements of mechanical parameters where it is important to reduce series compliance artifacts. If all the sarcomeres in a given preparation were truly homogeneous, SL and FL control would be effectively synonymous.

Tension control. When SLControl was first conceived, the sole aim of the project was to provide a means of controlling SL in real-time during precise measurements of muscle stiffness. It soon became apparent, however, that the framework necessary for such a task could easily be adapted to perform tension

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**Fig. 4.** Example recordings made with and without SL control. Permeabilized canine myocardial preparation submaximally activated in pCa (= −log10(Ca2+)) 6.0 solution, i.e., steady-state isometric tension is ~0.06 of the maximal Ca2+-activated value. Temperature = 15°C. The horizontal dashed lines represent the prevailing FL and SLs at the beginning of each record. The vertical dashed lines mark the initiation of SL control. Note that FL is maintained at the end of the record made under FL control, whereas SL is maintained under SL control. Although the experimental records made under SL and preparation length control are qualitatively similar, there are important quantitative differences between the traces. For example, the initial stiffness values of the muscle during the first stretches correspond to Young’s moduli of 114 kN/m² (preparation length control) and 152 kN/m² (SL control) (calculated from the gradients of regression lines fitted to XY plots of force against SL for the first 100 ms of each lengthening response). The values are different by ~30%. The disparity is largely attributable to the effect of series compliance in the muscle attachments. These recordings were obtained during the course of experiments described by Campbell et al. (2) and are examples of the first published mechanical measurements of cardiac preparations made under real-time SL control.
control experiments as well. All that needed to be added to the existing software was a new user dialog showing the appropriate set of experimental parameters and a new DAPL algorithm. The necessary modifications were completed in a small fraction of the time that was required to develop the initial system.

Most of the users who employ the software’s tension control capabilities will probably investigate the force velocity and power-load relationships of activated muscles during episodes of loaded shortening (Fig. 5). However, the system can also be used to explore different aspects of muscle’s mechanical properties. We, for example, have used SLControl to record the nonlinear increase in SL observed when activated cardiac preparations are subjected to slowly increasing loads (2). Experiments of this type can reveal important information about muscle’s viscoelastic properties, which are not readily apparent in the length control regime.

The DAPL algorithm used for tension control is straightforward. The measured tension is simply compared with a target level, which was precalculated before the experimental recording initiated. If the measured value exceeds the target, the muscle is shortened; if it is less than the target, the muscle is lengthened. While this general approach is very similar to that discussed earlier for SL control (Fig. 3), there is an important difference in the way that the two types of experiments are carried out.

In length control experiments, there is a roughly linear relationship between the actuator position and the mean SL of the preparation. The appropriate calibration factor can be found from preliminary test measurements and remains approximately constant irrespective of the level of contractile activity. This is markedly different from the situation encountered in tension control experiments where there is no straightforward relationship between actuator position and muscle force. Certainly tension will drop in phase with the movement if the muscle is rapidly shortened, but it will redevelop at a characteristic rate thereafter. Moreover, the magnitude of the tension drop will depend on the muscle’s level of contractile activity, being quite small in the case of partially activated fibers and quite large under conditions of maximal activation.

The implication of this is that there is no one value of proportional gain that produces adequate servo control in different types of tension control experiment. Instead, the gain factor (i.e., the ratio defining the extent of actuator movement for a given difference between measured and desired force values) must be adjusted between experiments to produce optimal results. In the records illustrated in Fig. 5, for example, a higher gain was required for the experiments holding force at low levels (where the muscle is shortening rapidly and is consequently relatively compliant) than for the experiments holding force nearer the isometric level.

Although this procedure sounds quite complicated, suitable values for proportional gain are easily deduced in preliminary measurements. Our experience also suggests that once established, appropriate relative gain values remain quite consistent between different experimental preparations. SLControl has thus been adapted so that it can automatically impose different sized tension releases with preset relative gain values. The records shown in Fig. 5 were obtained using just such a procedure.

Further information relating to tension control measurements and example recordings obtained with different values of proportional gain are available at http://www.slcontrol.com.

Other considerations. SLControl’s experimental protocols allow the user to select an appropriate sampling rate from a list of predefined values. These range from 100 to 2,500 Hz for length control measurements and from 100 to 5,000 Hz for tension control measurements. The sampling rate defines not only the speed at which new data points are acquired but also the frequency at which the motor command signal is updated under closed loop control. At the maximum sampling rate of 5 kHz (tension control mode) the motor command signal will thus be updated at regular time.

Fig. 5. A: tension control measurements from a maximally Ca\textsuperscript{2+}-activated permeabilized rat soleus muscle fiber. The fiber was held at its initial length for 100 ms and then allowed to shorten under constant loads ranging from ~8 to ~80% of maximal isometric tension. After a further 100 ms, the fiber was shortened to 80% of its original length, held at this short length for 20 ms and then rapidly reextended. B: plots of shortening velocity and power output expressed as functions of maximal isometric tension. Temperature 15°C, initial SL ~2.6 μm. Records provided courtesy of D. P. Fitzsimons (our laboratory). SLControl can also record the extent of sarcomere shortening during tension control measurements if a suitable detection system is available. Such recordings can be used to compare the power output of the overall preparation to that of individual sarcomeres.

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intervals of 0.2 ms. Optimal performance therefore requires a force transducer with a frequency response which extends to at least 2.5 kHz.

Those contemplating using such equipment are reminded that the standard DAP 5216a board does not incorporate analog filtering. Users should therefore ensure that the output signals from their force transducer and SL detection system are low-pass filtered below the appropriate Nyquist frequency (half the corresponding sampling rate) to prevent aliasing.

SLControl assumes that the 16-bit DAP board is installed in its default configuration with analog input ranges of ±5 V. Although this corresponds to an analog-to-digital conversion resolution of ~0.15 mV, users are encouraged to apply appropriate signal conditioning so that the acquired signals span as much of the input range as possible. A similar consideration applies to the DAC1 output, which controls the length actuator. Those using custom-built motors should ensure that the input range of their actuator matches the DAP’s ±5 V output capabilities.

Analysis/data export. SLControl provides several options for analyzing previously acquired data. Probably the most useful is a simple dialog, which displays a specified record and allows the user to read off the values of individual data points using appropriately labeled cursors. A variety of curve-fitting tools are supplied for parameter estimation. Digital filters can also be applied to selected regions of the acquired data.

A more elaborate dialog allows the user to superpose up to 20 experimental records. This feature has proved to be of particular use in pilot experiments where it can be helpful to visualize the effects of changing a selected experimental parameter. Finally, SLControl provides several batch analysis options that enable the user to repeat the same analysis task on a list of data files without continual intervention. This feature greatly reduces the effort required to analyze large data sets.

SLControl stores data records in a simple ASCII format. It is thus perfectly feasible to import raw data records straight into commercial spreadsheets and/or graphing software. An alternative is to use SLControl’s output routines, which automatically analyze the header information stored within each data file and output columns of calibrated data (i.e., tension values expressed in units of N/m², muscle length in meters, etc.). Analysis views can also be exported in a meta file format for rapid transfer to presentation software.

In summary, SLControl appears to be the first control software that has been freely distributed to the muscle physiology community. The system has many useful features, but its most important advantage is that it provides the experimenter with an integrated suite of experimental protocols and analysis tools. Users can now perform a wide variety of measurements on the same muscle sample, implementing FL, SL, and tension control as appropriate to probe the mechanical properties of their preparation. This newfound flexibility may prove important for future developments in muscle physiology.

SLControl does not require additional analog circuitry, is easy to install on any Windows-based PC, and has already been used successfully in several different laboratories. Together, these features suggest that SLControl may prove to be a useful tool for those engaged in muscle mechanics experiments. The software is available as a free download (for noncommercial use) at http://www.slccontrol.com.

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DISCLOSURES

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