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Evaluation of a self-consistent method for calculating muscle parameters from a set of isokinetic releases

Jan Peter van Zandwijk, Guus C. Baan, Maarten F. Bobbert, Peter A. Huijing

Institute for Fundamental and Clinical Human Movement Sciences, Faculty of Human Movement Sciences, Vrije Universiteit, Van der Boechorststraat 9, 1081 BT Amsterdam, The Netherlands

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Abstract. A new method for calculating parameters describing the force-velocity relationship of the contractile element and the force-extension relationship of the series elastic element of skeletal muscle from a set of isokinetic release contractions is evaluated using experimental and numerical techniques. The method calculates from the set of isokinetic releases those force-velocity and force-extension relationships that give a self-consistent description of the data set. The self-consistent calculation method is applied to data obtained from the gastrocnemius medialis muscle of the rat, since for such an animal model both relationships can be independently derived from a set of isotonic release contractions. For the two animals studied, the force-velocity and force-extension relationships calculated by the self-consistent method were in good agreement with the ones derived from isotonic releases performed on the same muscle. The statistical properties of the estimates obtained by the calculation method were investigated using a Monte Carlo technique. The method was found to yield results which were biased by less than 2% and which possessed a coefficient of variation smaller than 5%. These findings indicate that the proposed calculation method can be a useful tool for determining the contractile properties of skeletal muscle as reflected in the force-velocity and force-extension relationships.

1 Introduction

When devising models of human muscle to be used in predicting mechanical output during explosive movements, it is especially important to obtain a good estimate of contractile behaviour of the muscle-tendon complexes (MTCs) involved in the movement. Within the classical structural model of Hill (1938), this behaviour is characterized for each MTC by the force-velocity (F-v) relationship of its contractile element (CE) and the force-extension (F-u) relationship of its series elastic element (SEE). For isolated skeletal muscle, both relationships can readily be derived from a set of isotonic release contractions (e.g. Jewell and Wilkie 1958; Van Zandwijk et al. 1996). In such contractions, MTC force is allowed to reach an isometric level before shortening against a constant load occurs.

To determine contractile behaviour of human muscle in vivo, many researchers have performed experiments on various muscle groups using isokinetic dynamometers. In these experiments, a joint is rotating at a constant angular velocity, leading to an approximately constant velocity of shortening of the agonist MTCs crossing the joint. This type of contraction has the advantage that one does not have to correct for inertial forces since imposed velocity is constant. As in isolated skeletal muscle, it is important to standardize the level of activation of CE across the range of imposed velocities studied. This can be achieved by letting active state and therewith force develop to an isometric level before allowing joint rotation. Such contractions will be referred to as isokinetic release contractions.

In this paper we will address the issue of how to obtain estimates of the F-v and F-u relationships from a set of isokinetic release contractions and will propose a method that simultaneously calculates both relationships from such a data set. To evaluate the performance of the method, it will be applied to isokinetic release contractions obtained from rat muscle in situ. Subsequently the F-v and F-u relationships calculated by the method are compared with those calculated from isotonic release contractions performed on the same muscle. In order to evaluate the performance of the method, a Monte Carlo study will be performed, in which the statistical properties of the estimates obtained by the method are examined. It is important to perform such an evaluation, since it is known that non-linear estimation methods can yield results that are strongly biased and have large variance (i.e. Bard 1974; Ratkowsky 1983).

2 Methods

2.1 Determination of F-u and F-v relationships from isokinetic release contractions

Figure 1 shows schematically the Hill-type muscle model used in this study. Besides CE and SEE, the model also contains a parallel elastic element

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Correspondence to: J.P. van Zandwijk (Tel: +31-20-4448475, Fax: +31-20-4448529, e-mail: j_p_van_zandwijk@fbw.vu.nl)

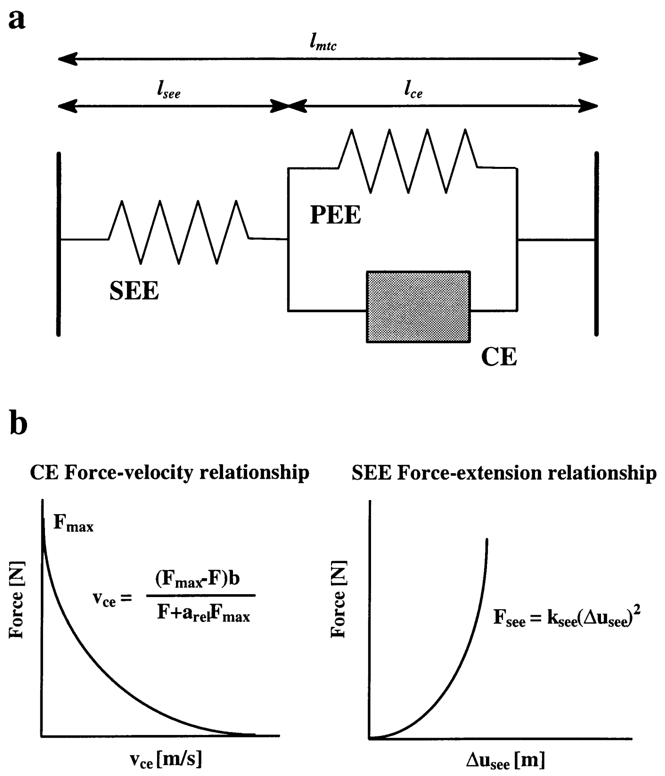

Fig. 1. a Schematic view of the arrangement of the contractile element (CE), series elastic element (SEE) and parallel elastic element (PEE) with respect to each other. The length measures used in this study are indicated. Note that, in all cases, PEE length equals CE length. **b** Relationships describing the force-velocity (F-v) relationship of CE and the force-extension (F-u) relationship of SEE

(PEE), representing the passive properties of muscle fibres. For the present study, these passive properties are of minor importance and will therefore be neglected in the following analysis. The SEE F-u relationship and CE F-v relationship as used in this study are shown as well and will be described below.

When CE is fully activated, its F-v relationship for shortening can be described by the hyperbolic Hill equation

$$v_{ce} = \frac{(F_{\max} - F)b}{F + a_{rel}F_{\max}} \tag{1}$$

Here, v_{ce} is the velocity of shortening of CE, F the force exerted by CE and $F_{\max}$ the maximal force CE can exert at a given length. The shape of the F-v relationship of CE is characterized by the value of the dimensionless parameter a_{rel} and the parameter b[m/s]. The parameter b can be expressed as $b_{rel} \equiv b/l_{ce,opt}$ [Hz], where $l_{ce,opt}$ [m] is the optimum length of CE, i.e. the length at which CE can exert its largest force. During an isokinetic release force is constantly dropping, indicating that SEE is shortening. This means that in order to obtain v_{ce} from the velocity of shortening of the MTC, v_{mtc}, one has to take into account the non-zero shortening velocity of SEE. This can be done if the F-u relationship of SEE is known. This relationship can be described by means of a non-linear spring

$$F = k_{see}(\Delta u_{see})^2 \tag{2}$$

where F is the force exerted by SEE, Δu_{see} the stretch of SEE and k_{see} [N/m^2] the stiffness constant of SEE. Using this relationship, v_{ce} can be calculated from v_{mtc} by means of

$$v_{ce} = v_{mtc} + \frac{\frac{dF}{dt}}{2\sqrt{Fk_{see}}} \tag{3}$$

The SEE F-u relationship can be obtained from an isokinetic release at such a high imposed velocity that force eventually drops to zero. In the literature this technique is often called the controlled-release technique (i.e. Hill 1950; Hof 1997). In this case, it is convenient to perform calculations in terms of imposed displacement, which is simply the time integral of the imposed shortening velocity. During the rapid isokinetic release, both SEE and CE shorten. Hence, in order to obtain the SEE F-u relationship from such a contraction, one must allow for the amount of displacement taken up by CE. This can be done, if the F-v relationship of CE is known (Hill 1950), by setting

$$\begin{aligned} \Delta u_{see} &= \Delta u_{mtc} - \int_0^{t_f} v_{ce}dt \\ &= \Delta u_{mtc} - \int_0^{t_f} \frac{(F_{init} - F)b}{F + a_{rel}F_{init}}dt \end{aligned} \tag{4}$$

Here, Δu_{mtc} is the displacement imposed on the MTC and t_f is the time at which Δu_{mtc} is attained, counted from the start of the release. F_{init} is the isometric force before the start of the release. Note that correcting the isokinetic release experiment this way is not strictly correct since it is assumed that maximal force $F_{\max}$ does not depend on CE length. However, the errors introduced by this assumption are small because the change of $F_{\max}$ with CE length is negligible for the contractions used in this study and therefore (4) is sufficiently accurate.

It is important to note that the SEE stiffness constant k_{see} appears in (3) and the CE force-velocity parameters a_{rel} and b appear in (4). Therefore the CE F-v and the SEE F-u relationships derived from a set of isokinetic release contractions are mutually dependent.

2.2 Self-consistent calculation method

Since the CE F-v and SEE F-u relationships are mutually dependent when derived from a set of isokinetic releases, one seeks to determine simultaneously those two relationships that give a *self-consistent* description of the data set. This means they must have the property that (i) when the isokinetic releases are corrected for non-zero SEE velocity using the SEE F-u relationship, the CE F-v relationship is obtained and (ii) when the rapid isokinetic release is corrected for CE shortening using the CE F-v relationship, the SEE F-u relationship is obtained. Figure 2 shows a calculation scheme that can be used to derive those F-v and F-u relationships from a set of isokinetic releases. Given an input vector of parameters $n \equiv (a_{rel}, b, k_{see})$ describing the CE F-v and the SEE F-u relationships, the parameters are recalculated from the set of isokinetic releases, yielding an output vector of parameters n_{out}. This means that the isokinetic contractions are corrected for SEE shortening velocity and the rapid isokinetic release for CE shortening using (3) and (4) respectively. Subsequently, the recalculated values of the parameters are obtained by fitting the models (1) and (2) to the corrected data using ordinary least squares. The objective of the self-consistent calculation (SCC) is to find iteratively a vector n for which the difference between n and n_{out} vanishes. In essence, this is the same as finding the root of the system of three non-linear equations $G(n) \equiv n_{out} - n$. Using n_{out} as input vector for the next iteration is numerically unstable and may lead to oscillations in the vector n, which can prevent convergence to a solution. A simple technique to damp these oscillations and to improve convergence, is to use a linear combination of input and output vector of the ith iteration to update the input vector for the next iteration (i.e. Isaacson and Keller 1966):

$$n^{(i+1)} = (1 - \alpha)n^{(i)} + \alpha n_{out}^{(i)} \tag{5}$$

The use of a small value of α (typically $\alpha \leq 0.2$) is sufficient to make the scheme from Fig. 2 converge to a solution.

2.3 Animal experiment

In order to test the performance of SCC, experiments were performed on the gastrocnemius medialis (GM) muscle of two adult Wistar rats. Guidelines and regulations according to Dutch law were followed to ensure animal welfare. The animals were anaesthesized with urethane (1.5 g/kg) injected intraperitoneally. The experimental method adopted was similar to the one described previously (Van Zandwijk et al. 1996). In short, the GM muscle

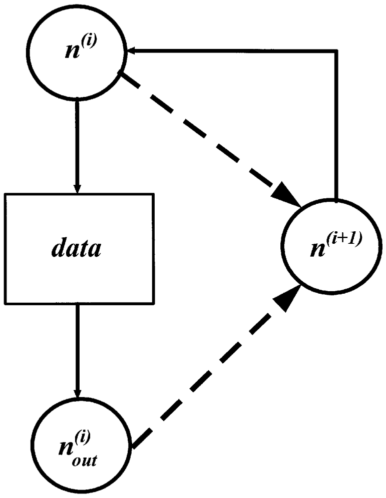

Fig. 2. Flow diagram of the self-consistent calculation method proposed in this study. The meaning of the symbols is explained in the main text

was exposed and freed from surrounding structures, leaving its blood supply intact. The calcaneus was cut and the Achilles tendon was looped with part of the calcaneus around a piece of steel wire and fixed to it by means of a ligature. The steel wire was connected to a force transducer. During experiments, muscle temperature was kept at 35°C using a feedback control system consisting of heating lamp and a thermosensor positioned close to the muscle. To prevent drying, the muscle was covered with a layer of paraffin oil.

The GM muscle was stimulated through its severed nerve using 3 mA square current pulses of 0.1 ms duration. Both isokinetic release contractions and isotonic release contractions were performed on a general-purpose muscle ergometer (Woittiez et al. 1987). In either case, tetanic contractions were elicited by stimulating the muscle at a frequency of 80 Hz for 500 ms, except for the isokinetic release contractions at the lowest velocities, where the duration of the stimulation interval was extended to 700 ms. Each tetanic contraction was preceded by a single twitch to let the muscle adapt to its new length. Tetanic contraction started 350 ms after the onset of the twitch and 150 ms after each tetanic contraction a second twitch was elicited. In both the isokinetic and isotonic experiments, contractions were initiated from a MTC length 2 mm larger than optimum MTC length and the GM muscle was stimulated for 350 ms isometrically before it was allowed to shorten. Between subsequent contractions, the muscle was allowed to recover for 3 min at slack length.

In the isokinetic release experiments ten velocities ranging between 10 mm/s and 200 mm/s were imposed on the GM MTC. The latter velocity is approximately equal to the maximal shortening velocity of the GM CE at this temperature and was used to obtain the SEE F-u relationship. The amplitude of the release was 3 mm for the lower velocities and 5 mm for the highest ones. In the isotonic release experiments, the GM MTC was allowed to shorten against loads ranging between approximately 10% and 90% of isometric force, starting with the highest loads and subsequently reducing the value of the load.

At the end of the experiment, the animal was killed and the GM muscle was removed from the body and fixed. Subsequently, the muscle was prepared for the collection of single muscle fibres using the method of Huijing (1985). Four fibres from the most distal part of the muscle were isolated and in each of them the number of sarcomeres in series was determined using a semi-automatic counting system (IBAS, Kontron Elektronik, Echting, Germany). Subsequently, optimum CE length was calculated by multiplying the averaged number of sarcomeres found in the four fibres by sarcomere optimum length. In this study a value for rat sarcomere optimum length of 2.4 μm was used (Zuurbier et al. 1995).

Finally, the value of parameters describing the CE F-v and SEE F-u relationships were derived independently from both the isotonic release experiments as described in Van Zandwijk et al. (1996) and the isokinetic release contractions using SCC.

2.4 Numerical experiment

To examine the statistical properties of the estimates obtained by the SCC method, a Monte Carlo study was performed. In this study, isokinetic release contractions of maximally activated rat GM muscle were simulated at the same imposed velocities as in the animal experiment, using a Hill-type muscle model that has been described extensively elsewhere (Van Soest and Bobbert 1993; Van Zandwijk et al. 1996). Subsequently, Gaussian-distributed pseudorandom noise was added to both force and displacement histories generated by the model. The noise present on the displacement history introduces scatter of both v_{ce} in (1) through the imposed velocity of shortening v_{mtc} in (3) and of Δu_{see} in (2) through the imposed displacement Δu_{mtc} in (4), while the noise added to the force history introduces scatter of the force F in both (1) and (2), all well as to v_{ce} and Δu_{see} through the terms containing F in (3) and (4). In total 500 different samples of pseudorandom noise were added to the simulated data sets and SCC was applied to each of these noisy data sets. Subsequently, the properties of the estimates of the parameters describing the F-v and F-u relationships found by SCC were determined.

3 Results

3.1 Animal experiment

Figure 3 gives a typical example of part of the force and velocity histories recorded during the isokinetic release experiments for one animal. In Fig. 4 the CE F-v and SEE F-u relationships calculated by SCC from the isokinetic releases are shown. This figure shows uncorrected data points as well as data points obtained by applying (3) and (4) to the data, using the CE F-v and SEE F-u relationships that give the final, self-consistent description of the set. The fit of models (1) and (2) to the corrected data is shown as well. Note that for the CE F-v relationship, the correction for non-zero SEE velocity increases with imposed velocity of shortening and can amount to 12% of the imposed velocity at the highest velocities. For the SEE F-u relationship, the corrections for CE shortening during the rapid release are quite substantial, due to the fact that maximal CE shortening velocity is of the same order of magnitude as the imposed velocity of shortening. Figure 5 compares for the same animal the CE F-v and SEE F-u relationships found by SCC with the ones obtained from isotonic releases. The figure shows the fits of models (1) and (2) obtained by the two methods. Finally, Table 1 compares for both animals the parameter values describing the CE F-v and SEE F-u relationships as calculated from isokinetic releases using SCC with the ones derived from isotonic releases. To facilitate comparison between the animals, the constant b in the CE F-u relationship is expressed in optimum CE lengths/s. Parameter values obtained by the two methods are in good agreement with each other. To better appreciate this, one must realize that the two methods for obtaining an estimate of the SEE F-u relationship are fundamentally different. In SCC, this relationship is obtained from a *single* release at a high imposed shortening velocity, while in the isotonic release experiments this relation is obtained by a fitting procedure applied to combined data from *a number of* isotonic releases, each to a different load (e.g. Van Zandwijk et al. 1996).

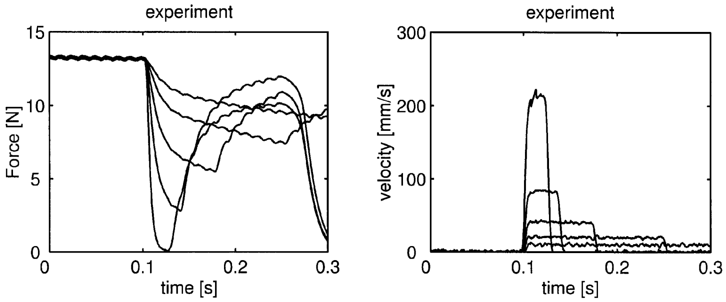

Fig. 3. Typical example of force and velocity histories recorded during isokinetic release contractions performed on the gastrocnemius medialis muscle of the rat. Left: Superimposed force histories recorded at shortening velocities of 10 mm/s, 20 mm/s, 40 mm/s, 80 mm/s and 200 mm/s (from *top* to *bottom*). The traces corresponding to imposed velocities of 10 mm/s and 20 mm/s are from contractions in which stimulation duration was increased by 200 ms. Initial isometric tension development is not shown. Note isometric redevelopment of tension after the MTC has completed shortening. Right: Corresponding velocity histories. Note that for the fastest movement, the imposed velocity is slightly larger than 200 mm/s. Not all data used as input for the self-consistent calculation (SCC) are shown

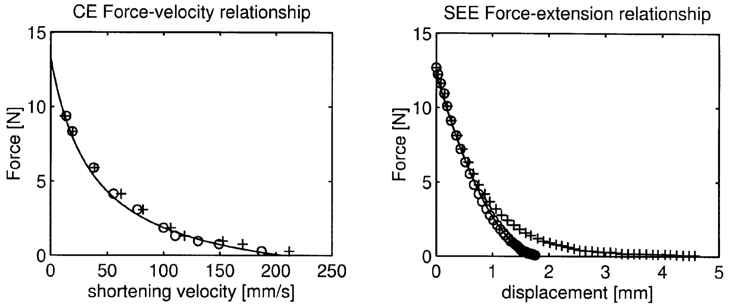

Fig. 4. Results of the SCC method applied to data, part of which is shown in Fig. 3. Shown are experimental data points (*crosses*) and points obtained by applying (3) and (4) to the data (*circles*) using those CE force-velocity and SEE force-extension relationships that yield the self-consistent description of the data set. The *continuous lines* are the fit of models (1) and (2) to the corrected data points. For the F-v relationship, all data points pertain to the same CE length. Left: CE F-v relationship. Right: SEE F-u relationship

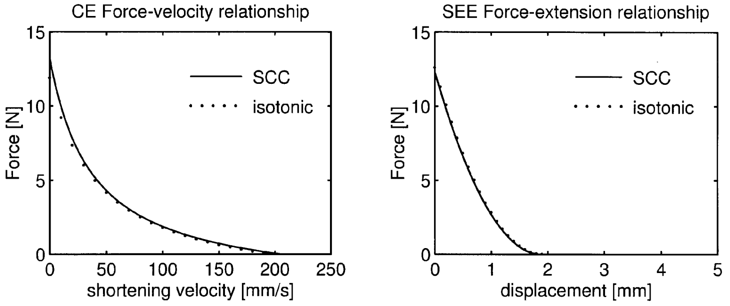

Fig. 5. Comparison between the CE F-v and SEE F-u relationships obtained from isokinetic releases by SCC and from isotonic releases. Shown are the fits to the models (1) and (2) for either method. Left: CE F-v relationship Right: SEE F-u relationship

Table 1. Values of parameters describing the contractile element (CE) force-velocity and series elastic element (SEE) force-extension relationships

	Animal 1		Animal 2	
	SCC	Isotonic	SCC	Isotonic
k_{see} [N/m^2]	3.61×10^6	3.49×10^6	3.33×10^6	3.61×10^6
a_{rel}	0.18	0.2s3	0.20	0.17
b_{rel} [Hz]	2.83	3.32	3.12	2.76
$l_{ce,opt}$[m]		0.0134		0.0150

The parameters a_{rel} and b_{rel} pertain to the CE force-velocity relationship, while the parameter k_{see} pertains to the SEE force-extension relationship. The optimum length of CE, $l_{ce,opt}$, is calculated from the averaged number of sarcomeres in four muscle fibres and the optimum length of rat sarcomeres of 2.4 μm (Zuurbier et al. (1995))

Table 2. Results of the Monte Carlo study

Parameter	Bias [%]	CV [%]
k_{see} [N/m^2]	1.47	1.78
a_{rel}	0.26	4.12
b [m/s]	1.59	2.88

Bias is expressed as a percentage of the parameter values used to construct the data. The coefficient of variation (CV) is the standard deviation of the estimates normalized with respect to the averaged value of the estimates

3.2 Numerical experiment

Figure 6 gives an example of the force and velocity histories that were used as input data for the SCC in the Monte Carlo study. The data are generated by the Hill-type muscle model, using the CE F-v and SEE F-u relationships from the first animal as derived from the isotonic release contractions. The traces shown are at the same imposed velocities as the experimental results shown in Fig. 3. Note the noise present on both the force and the velocity histories. The amplitude of the noise amounted to 0.15% of maximal force and 0.015% of optimum MTC length, which is in both cases an estimate of the amount of noise present in the experimentally recorded data (cf. Fig. 3). Next, the CE F-v and SEE F-u relationships were recalculated 500 times from the noisy data by SCC, each time using a different sample of pseudorandom noise. Figure 7 shows scatter plots of the parameters describing the F-v and F-u relationships as obtained in these runs. Each parameter is shown as the relative amount by which it deviates from the value used to construct the data set. Zero deviation is indicated by continuous lines. As can be seen from the figure, SCC yields, for the data sets studied, estimates of the parameters which are biased by less than 2%. To assess the variance of the estimates, we calculated coefficients of variation. These were smaller than 5% for all three parameters. Table 2 summarizes the results of the analysis of the estimates. Of course, the performance of SCC depends on the amount of noise added to the data as well as on the data used as input for the SCC. Nevertheless, at the noise level studied, which approximates the amount of

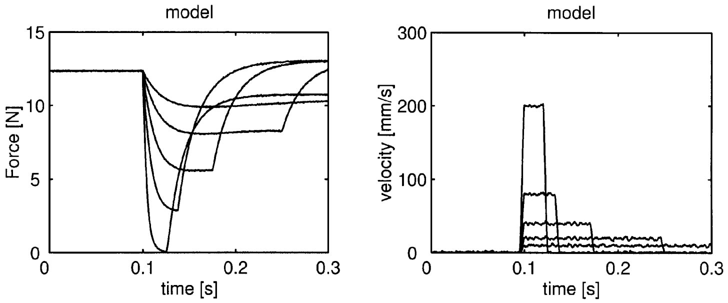

Fig. 6. Example of some of the simulated isokinetic release contractions used as input for the SCC. Note the pseudorandom noise present in the force and velocity histories. Simulated shortening velocities are the same as in Fig. 3. Left: Force histories. Right: corresponding velocity histories

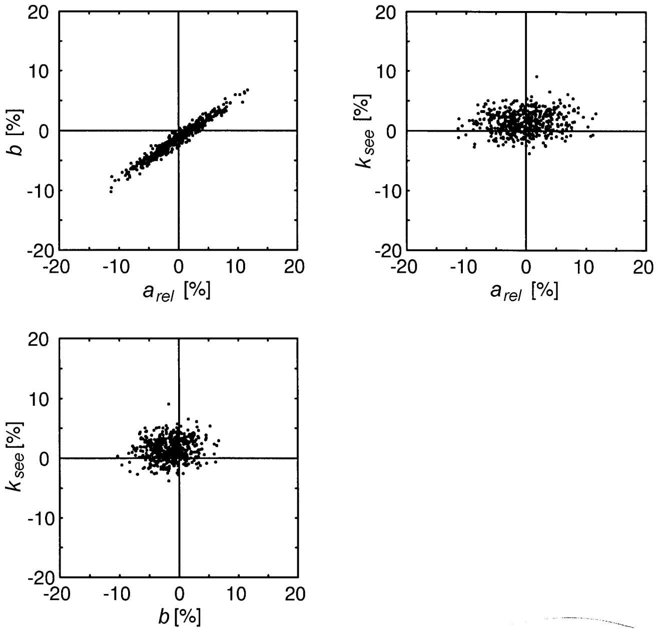

Fig. 7. Scatter plots of the parameters values obtained in the Monte Carlo study by applying SCC to data generated in model calculations with pseudorandom noise added to both force and displacement histories. Parameter values are expressed as the relative amount by which they deviate from the value used to generate the data sets. Zero deviations are indicated by *continuous lines*. The parameters a_{rel} and b describe the CE force-velocity relationship, while the parameter k_{see} describes the SEE force-extension relationship

noise present in the experimental data, the results shown in Fig. 7 indicate that the estimates obtained by SCC are neither strongly biased nor possess extremely large variance.

4 Discussion

In this study we set out to examine the feasibility of a self-consistent calculation method for obtaining estimates of parameters describing the CE F-v relationship and the SEE F-u relationship from a set of isokinetic release contractions. For this purpose, the method was applied to data obtained from the GM muscle of the rat. The results presented in Fig. 5 and Table 1 indicate that the CE F-v and SEE F-u relationships found by SCC were in good agreement with the ones found by a conventional isotonic release technique. Differences in parameter values between the two methods are comparable to differences in parameter values due to noise on the input data, as observed in the Monte Carlo study. The Monte Carlo study further revealed that the estimates were biased by only 2% and possessed a coefficient of variation smaller than 5%, which seems to be small enough for practical purposes.

These results gives confidence that the SCC method can be a useful tool for deriving parameter values describing the CE F-v and SEE F-u relationships. For this purpose, it requires a set of isokinetic release contractions at imposed velocities up to approximately the maximal shortening velocity of the CE of the muscle studied. For isolated skeletal muscle, this usually does not present too many difficulties. For human muscle in vivo, however, standard isokinetic dynamometers are usually not fast enough to achieve this goal. However, it has recently been shown by Hof (1997) that it is possible to design special-purpose dynamometers that are indeed capable of achieving such high imposed shortening velocities that force eventually drops to zero. With the use of such dynamometers, it becomes possible to obtain isokinetic release data on human muscle that will allow computation of the CE F-v and SEE F-v relationships using SCC.

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References

Bard Y (1974) Nonlinear parameter estimation. Academic Press, New York

Hill AV (1938) The heat of shortening and the dynamic constants of muscle. Proc R Soc Lond B 126:136–195

Hill AV (1950) The series elastic component of muscle. Proc R Soc Lond B 137:273–280

Hof AL (1997) A controlled-release ergometer for the human ankle. J Biomech 30:203–206

Huijing PA (1985) Architecture of the human gastrocnemius muscle and some functional consequences. Acta Anat 123:101–107

Isaacson E, Keller HP (1966). Analysis of numerical methods. Wiley, New York

Jewell BR, Wilkie DR (1958) An analysis of the mechanical components in frog's striated muscle. J Physiol (Lond) 143:515–540

Ratkowsky DA (1983) Nonlinear regression modeling: a unified practical approach. Dekker, New York

Soest AJ van, Bobbert MF (1993) The contribution of muscle properties in the control of explosive movements. Biol Cybern 69:195–204

Woittiez RD, Brand C, de Haan A, Hollander AP, Huijing PA, Van der Tak R, Rijnsburger WH (1987) A multi-purpose muscle ergometer. J Biomech 20:215–218

Zandwijk JP van, Bobbert MF, Baan GC, Huijing PA (1996) From twitch to tetanus: performance of excitation dynamics optimized for a twitch in predicting tetanic muscle forces. Biol Cybern 75: 409–417

Zuurbier CJ, Heslinga JW, Lee-de Groot MBE, Van der Laarse WJ (1995) Mean sarcomere length-force relationship of rat muscle fibre bundles. J Biomech 28:83–87