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The effect of measuring device and method of calculation on the leg extension torque-velocity relationship

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Abstract The aim of this study is to compare the computational methods for extracting force/torque-velociy data, and the results using an isokinetic device and a pneumatic device. We have compared the methods using the average torque, the peak torque, and the torque at a predefined angle. Since the same participants perform on different devices it becomes possible to check the consistency of the constructed torque-velocity curves. The data for the isokinetic device and the pneumatic device did overlap to a degree – the maximum velocity for the isokinetic device was around 300 deg s^{-1} while the minimum velocity for the pneumatic device exceeded in general 200 deg s^{-1}. It was however difficult to fit the isokinetic and pneumatic data to the same torque-velocity curve defined by the Hill-equation. This is apparently an effect of the different dynamical constraints imposed by the devices with the result that their data cannot be intepreted exactly in the same manner. For the pneumatic device the peak torque method seems to be a robust method for extracting the force-velocity data. It is suggested that measuring the fraction T_{pp}/T_0 of the torque T_{pp} at the point of peak power to the MVC isometric maximum torque T_0, as well as the corresponding angular velocity ω_{pp} at peak power, could provide measures for monitoring the force-velocity properties of the leg extensors. This requires however that the force-velocity data covers velocities above ω_{pp} which is around 35-40% of the maximum contraction velocity ω_0 around 1000 deg s^{-1}.

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Key words Force-velocity relation – Leg extension – Isokinetic device – Pneumatic resistance device – Hill-equation

1 Introduction

Determining the force-velocity, or the torque-velocity ($T - V$) relationship, is one of the classical problems in biomechanics. The basic mathematical model has been given by Hill (1938). The relationship is similar if single muscle fibre (Edman et al, 1978; Julian and Morgan, 1979), isolated muscle (Hill, 1938) or intact muscle groups have been examined (Komi, 1973; Tihanyi et al, 1982; Wilkie, 1950). However, applying the model to concrete cases, such as leg-extension might not be that straightforward. Indeed, given experimental data obtained by a leg-extension device, the question arises about how to extract the $T - V$ parameters. Apparently the torque-velocity relationship can be constructed in various ways depending on how one extracts the representative torque-velocity pairs from the data; for example, taking torque at a specific angle (Finni et al, 2003), the peak torque (T_{pt}, ω_{pt}), or at the point of peak power (T_{pp}, ω_{pp}). One might expect that the optimal method for determining the torque-velocity relation depends on the sort of device used.

One important point is that leg-extension measurements with isokinetic devices are usually restricted to velocities around 5 rad s^{-1} ($\approx$ 285 deg s^{-1}) or smaller, while e.g. the inertial resistance machine (Tihanyi et al, 1982) is usually restricted to velocities *above* 5 rad s^{-1}. Therefore torque-velocity data based on these devices will barely overlap. Furthermore, as pointed out by Rácz et al (2002), most investigators using isokinetic devices have found their results difficult to reconcile with the Hill-curve. On the other hand for example Tihanyi et al (1982) find a quite good match with the Hill-curve using dynamical resistance devices. One may therefore wonder whether the "problem" with the isokinetic devices indicates that the Hill-relation is invalid for low velocities (Edman, 1988, 2005), or that there is something wrong with the analysis or the measurement method. Thus, it is claimed (Rácz et al, 2002) that by using average torque in the construction of the torque-velocity curve one may reconcile the isokinetic data with the Hill-curve. One argument offered is that the mean torque represents a measure of the "working capacity" of the muscle that can be related to the $b(F_0 - F)$ term in the Hill-equation supposedly describing the rate of doing work (power). It is not entirely clear to us how this argument can show that the averaging method is able to better extract the Hill-parameters from the data. The mean value method however seems to make the data usually more "Hill-friendly" but in our case it did not amend the data-Hill discrepancies that we found for a part of the tests. We tested the mean value method also for the pneumatic device as a computational method. Since for the pneumatic device the load is preset and the velocity varies, the mean value method has a different meaning in this case compared to the case with the isokinetic device.

A further general complication arises from the fact that not only do the results depend on the computational methods but also on the measurement protocols, such as using the release method, normal voluntary control, or stimulated leg-extension (James et al, 1994). In the paper we include some estimates how gravity and the time of veloctiy development may affect the results too. Also some theoretical issues regarding the Hill-equation are discussed; e.g., how is the isometric MVC force related to the equation?

2 Methods and materials

2.1 Data collection

Sixteen healthy subjects (8 male, 8 female) volunteered for this study. The subjects signed informed consent after the measurement protocols were explained. The female subjects were 25.1 ± 2.4 years (mean ± SD), 64.0 ± 10.3 kg and 170.5 ± 6.9 cm and male subjects 25.6 ± 1.9 years, 83.5 ± 8.6 kg and 180.6 ± 4.1 cm, respectively. Subjects were informed to avoid heavy physical activity two days before measurements. The subjects performed the tests with the two devices (isokinetic and pneumatic device) on separate days. On both devices the subjects performed 2-3 maximal isometric knee extensions at a knee angle of 120 degrees and the best result was considered to be the effective maximum voluntary contraction (MVC). After measuring the MVC, the subjects performed several dynamic knee extensions. With the pneumatic device maximum dynamic extensions were made with seven different loads, starting with a resistance of 2 bars and finishing at 8 bars resistance with 1 bar increments (the load varying from ca 60 to 120 Nm). With the isokinetic device the subjects performed 1-2 maximal dynamic extensions with 3 different velocities (73 deg s^{-1}, 183 deg s^{-1}, 293 deg s^{-1}). The order of velocities was randomly selected. The isokinetic device employs a manual release mechanism which sets the lever arm into motion only when the force reaches a predetermined fraction of the MVC, and then accelerating with 5730 deg s^{-2} (= 100 rad s^{-2}) till the nominal velocity is reached. In addition the participants performed MVC knee extensions on a weight stack device (David 200) for seven different loads in the range 20 – 80 kg. The data was very difficult to analyze for T-V purposes, underscoring the effect of device dynamics on the performance, and will be only briefly presented.

The resistance in the pneumatic device (Hur Co, Kokkola, Finland) is produced by a pneumatic cylinder attached to a lever arm. During the range of movement the lever arm rotates and the changing geometry produces a curvlinear resistance curve with the peak at a knee angle of approximately 130 degrees. Because there is no weight stack the inertial effects are determined by the lever arm system and the leg alone. The moment of inertia I = 0.4 kg m^2 of the lever arm (plus the foot support) is about the same as that of the shank plus the foot for a typical adult. Maximum acceleration at the beginning of the movement may be of the order of 100 rad s^{-2} implying an inertial resistance around 40 Nm. The inertial effect falls off rapidly when the velocity reaches a "flat region" (within ca 50 ms). The isokinetic device (Komi et al, 2000) is driven by a powerful servomotor that allows high acceleration. In both devices the force is measured with a strain gauge transducer in the lever arm to which the the subject's leg is strapped.

Torque and joint angle were sampled with the rate of 1000 S/s for the isokinetic device, whereafter a 5-point average was applied resulting finally in 200 samples per second. The pneumatic device uses a sampling rate of 2000 S/s and a 10-point averaging resulting also in a final effective sampling rate of 200 S/s. Representative joint angular velocity ω and knee extension torque T were obtained from the data according to the following four methods:

1. as the torque T_{120} and the velocity ω_{120} at the 120° knee joint angle
2. as the peak torque T_{pt} and the corresponding velocity ω_{pt} (for the isokinetic device we calculated the peak torque after dropping the initial 125 ms section of the data)
3. as the torque T_{pp} and the corresponding velocity ω_{pp} at the peak power (power given by $P = T \cdot \omega$)
4. finally as the mean torque T_{m} and the mean velocity ω_{m} in the 90°-170° range.

The $T - V$ relationships were then constructed based on the calculated results. Note that methods 2 and 3 in general produce identical results for the isokinetic device since the maximum power will correspond to the maximum torque when the velocity is constant.

2.2 Theory

2.2.1 Hill-relations Empirical force-velocity relations are obtained by plotting force vs velocity. It seems that a natural consequence of physiology and biomechanics is that the MVC force F has to be a decreasing function of the contraction velocity V. According to the standard crossbridge model (Huxley, 1957) the force decrease is caused by a form of slipping. As the thick and thin filaments are sliding past each other (in concentric motion) the springlike force on the thin filament decreases. For a given muscle length the empirical Hill-relation states that,

$$\frac{F}{F_0} = \frac{1 - \frac{V}{V_0}}{1 + c\frac{V}{V_0}}, \tag{1}$$

$$\frac{V}{V_0} = \frac{1 - \frac{F}{F_0}}{1 + c\frac{F}{F_0}}, \tag{2}$$

where F_0 is the MVC isometric force, and V_0 the maximum contraction velocity. The *shape parameter* c determines the curvature of the Hill-curve (it is related to the standard Hill-parameters a and b by $c = F_0/a = V_0/b$). Note that, since we use scaled variables F/F_0 and V/V_0 we can interchangeably use scaled torque T/T_0 and angular velocity ω/ω_0 because these ratios are equivalent as the moment arm drops out when computing the ratios. This is based on the further assumption that the moment arm does not vary too much with force. (The variation of the moment arm with joint angle is not so serious since the torque and the velocity are used in a somewhat narrow joint angle range around 120°-130°. Typically the moment arm at the patella is about 3.3 cm.) We may also note that Edman (1988, 2005) has proposed a "double-hyperbolic" force-velocity relation, with the normal Hill-hyperbola covering the range of 0%-80% MVC, and another hyperbola-like segment covering the range 80%-100% MVC. Edman fitted his (single fiber) data using an equation of the form

$$V = b\frac{F_0^\star - F}{F + a} \cdot \frac{1}{e^{k_1(F - k_2 F_0)} + 1}, \tag{3}$$

where the first factor corresponds to the Hill-equation, and the second factor is a "correction" term that will contribute to a noticeable deviation from the Hill-equation for $F > 0.8 \cdot F_0$ when k_2 is around 0.85. Edman interprets F_0 as the measured MVC isometric force, whereas the value $F_0^\star$ to be used in the Hill-equation was found to be approximately $1.4 \times F_0$. (In Eq.(3) V is not mathematically zero for $F = F_0$; thus, "zero" velocity is somewhat arbitrarily defined as a small number $V(F = F_0)$ whose smallness is guaranteed by the exponential factor in Eq.(3) if k_1 is large enough – Edman has used $k_1 \approx 24F_0^{-1}$.) If this result were generalized to macroscopic muscles it would mean that one should use the value $1.4 \times F_0$ in the Hill-equation instead of F_0. In case of macroscopic muscles there seems to be no established value for such a correction factor to be used in the Hill-equation whence we have simply normalized the torque in the present study with the isometric MVC torque without such a factor. A bigger concern seems to be to ensure that one really obtains valid MVC results in the measurements.

If we restrict ourselves to the range where the $F-V$ relation (1) may be assumed to be valid, then it predicts that the a maximum power ($P = F \cdot V$) will be attained when

$$\frac{F}{F_0} = \frac{V}{V_0} = \frac{1}{1 + \sqrt{1 + c}}. \tag{4}$$

A typical result is that $F/F_0 = V/V_0 \approx 0.35$, corresponding to $c = 2.5$, at the point of of maximum power (Herzog, 1994). In a previous leg extension study (Borg and Herrala, 2002) ($n = 25$, semipro hockey players) the average value of F/F_0 was indeed found to be 0.35 ± 0.06. The corresponding average velocity was 410 deg s^{-1} implying a maximum velocity of the order 410/0.35 deg $s^{-1} \approx 1170$ deg s^{-1}. This finding indicates that in leg extension tests one must reach quite high velocities, above ca 400 deg s^{-1}, in order to cover the point of maximum power. If the test method stays below this then it means that it will in general cover less than 35% of the (concentric) force-velocity curve.

Tihanyi et al (1982) reported that the force-velocity test differentiated a group A whose members had predominantly fast twitch (FT) fibers and a group B with predominantly slow twitch (ST) fibers. Expressed in terms of the shape parameter c they got for the averaged Hill-curves $c \approx 3.2$ and $\omega_0 \approx 1000$ deg s^{-1} for the A-group, and $c \approx 2.4$ and $\omega_0 \approx 800$ deg s^{-1} for the B-group. Mathematical models of the muscle based on the crossbridge theory, such as by Hoppensteadt and Peskin (2002), predict that the shape parameter c is independent of the the rate of crossbridge detachement which is supposed to characterize fast and slow muscles. Thaller and Wagner (2004) present some evidence that power athletes, who may be assumed to have a high percentage of FT fibers, have smaller c-parameters than endurance athletes. In a mixed muscle model (MacIntosh and Holash, 2000) the c-parameter was "arbitrarily" set to 2.50 for ST fibers and 2.22 for FT fibers. The main difference between ST and FT was attributed to the maximum contraction velocities $V_{\max}$, assumed to be in the interval 20% - 33% for ST fibers, and in the interval 60% - 100% for FT fibers, in terms of the absolute maximum contraction velocity V_0. Interestingly this seems to contradict the conclusion by Thaller and Wagner (2004) that FT fibers are *not* correlated with higher maximum contraction velocities. Anyway one may construct such lumped models based on model muscles satisfying the Hill-equation with different parameters. At least in the types of models considered by MacIntosh and Holash (2000) one may thus obtain results which deviate significantly from the simple Hill-curve. Indeed, if the model consists, as above, of a FT part and a ST part with vastly different velocity regimes, then this may produce a bend in the force-velocity relation around the transistion from the ST velocity regime to the FT velocity regime. Trying to fit a Hill-curve to such a set may force an excessive high c-parameter to accommodate the bend. In practice it seems more reasonable in such cases to try to find the point (ω_{pp}, T_{pp}) corresponding to the maximum power. In the models this depends in quite a robust way on the ST-FT proportion; the higher proportion of ST the smaller is ω_{pp}.

In the following we will however use the Hill-equation, with the parameters $c = 2.5$ and $\omega_0 = 1000$ deg s^{-1}, as a reference curve. Force-velocity data which are too widely off this "guideline" in the interval 20% - 60% of isometric MVC may be suspected to contain some systematic error.

2.2.2 Time of velocity development The simple model (1) assumes maximum contraction (activity $a = 1$), and neglects the time factor (the fact that force development takes time). The last factor can be avoided if there is enough time for the force development during the movement. Ensuring MVC is more tricky. Assuming we have MVC, then, how rapidly is it possible reach the maximum velocity? The general equation of motion for the leg extension can be written as,

$$I\ddot{\phi}(t) = T(a, t, \phi(t), \dot{\phi}(t)) + mgR_c \cos\phi(t) - M(\phi(t)). \tag{5}$$

Here we make the simplification that the joint angle ϕ is 90° when shank is aligned with the vertical line. I denotes the moment of inertia of the lower leg (shank plus foot), and $mgR_c \cos\phi$ is the gravitational moment of the leg. The muscular torque T is written as function of activity a, angle ϕ and angular velocity $\dot{\phi}$ $(= \omega)$; for a basic model see Nigg and van den Bogert (1994) which however neglects the activity factor a which is apparently assumed to be 1 throughout. (Concerning muscle activation it is estimated that all motor units are activated when the force reaches about 60% of isometric MVC; the force increase in the interval 60% - 100% is achieved by an increased firing rate of the active motor units (Herzog, 2000).) Finally M denotes the resistance of the device which is measured by the transducer. We consider the very simplest case where we assume a constant resistance M, whose fraction in terms of the isometric maximum is denoted $\mu = M/T_0$. Furthermore we neglect the gravity and the time of force development. The time t for reaching a certain fraction q of the maximum velocity achievable for that resistance (according to the Hill-relation (2)) will then depend on the characteristic time

$$\tau = \frac{I\omega_0}{T_0}, \tag{6}$$

through

$$(1 + \beta c) \cdot \ln\left(\frac{1}{1-q}\right) - \beta c \cdot q = (1 + c\mu) \cdot t/\tau, \tag{7}$$

where

$$\beta = \frac{1-\mu}{1+c\mu}. \tag{8}$$

For typical values $T_0 = 200$ Nm, $I = 0.5$ kg m^2, and $\omega_0 = 17$ rad s^{-1} we obtain $\tau \approx 43$ ms. According to this, reaching 80% of the theoretically attainable velocity would require from 154 ms for zero load to 52 ms for 35% load (see Table 1) assuming a shape parameter $c = 2.5$. This may be a conservative estimate since we have e.g. neglected the rate of force development (which in case of the release method can be neglected though) and muscle-tendon visco-elasticity. The table also shows the angle $\phi(t)$ covered in time t calculated by integrating Eq.(8) numerically. For the corresponding velocity to be achieved during a leg extension in the interval 90° - 130° the angle covered should not exceed 40°. From the table we may get an impression how, by reducing the resistance, it gets harder to reach the attainable velocity. We see that it for zero load ($\mu = 0$) would be hard to reach more than 60-70% of the maximum velocity before we are out of the optimal movement range. Our data shows data μ typically ranged in the interval 0.2 - 0.6 for the pneumatic device; for a 20% load one may perhaps achieve 85% of the attainable velocity according to the model so we do not yet expect a major effect. Besides the time of force development one has to recognize another possible time-effect; namely, the effect of the time history on the contractile state (Herzog, 2000).

The previous analysis applies to the pneumatic device and also to inertial devices. (In the later case μ is set to zero in Eq.(7) and I is replaced by $I + kI_{\text{disk}}$ where I_{disk} is the moment of inertia of the rotating disk used as the inertial resistance. The factor k is the "gear" ratio between the angular velocity of the disk and the velocity of the leg.) The isokinetic device has a different dynamics since the velocity $\omega(t)$ and the angle $\phi(t)$ are preset as functions of time. Furthermore, for the isokinetic device the movement started with maximum preactivation which was not the case for the pneumatic device. A central issue is then whether the participant is able to keep up MVC during the movement.

2.2.3 Gravity effect In connection with Eq.(5) we already referred to the gravitational torque -$mgR_c \cos\phi$. A typical value mgR_c for a model person (mass = 80 kg, length = 180 cm) is 13 Nm according to the anthropometric models used by Winter (2005). At the angle $\phi = 130°$ its magnitude reduces to $|mgR_c \cos\phi| \approx 8$ Nm. If the isometric maximum is around 200 Nm then this gravitational component amounts to 4%. The effect is amplified for small relative loads. As an example, if $\tilde{\mu}$ is the true (gravity corrected) normalized torque and μ the one based on uncorrected torque values, then

$$\tilde{\mu} = \frac{20\mu + 1}{21} \approx 0.95\mu + 0.05, \tag{9}$$

in the case of $T_0 = 200$ Nm, and with a gravitational torque 10 Nm (at a fixed angle). In this (typical) case the true ratio $\tilde{\mu}$ is underestimated by 10% at $\mu = 0.3$, and by ca 20% at $\mu = 0.2$.

In the present case, neither isokinetic nor pneumatic device data have been "gravity corrected" if not stated otherwise. This does not affect the comparison between the devices. The effect on fitting the Hill-curve is also quite slight (in comparison with many other factors), since for our data the normalized μ-values are regularily larger than 0.2 and typically in the interval 0.25 – 0.6. However, one must be aware of the possibility of having a number of "small effects" that may add up constructively resulting in a signifcant sum total effect.

3 Results and discussion

Figures 1 (small resistance, 2 bars) and 2 (heavy resistance, 8 bars) show typical variations of force and joint angle during a MVC leg extension using the pneumatic device. Figure 3 shows an example with the isokinetic device. The large force peak in Fig. 1 is caused by the stopper at the end of the range of motion and does not influence the results. We can see that there is a rapid increase in the force at around $t = 600$ ms till the preset resistance level is reached. In the heavy load case (Fig. 2) the stopper peak is very much reduced. The force reaches the resistance level at $t = 250$ ms, and starts to drop after $t = 500$ ms till the stopper causes a bounce (around $t =$ 650 ms). The dynamics of the isokinetic device is somewhat different (Fig. 3; 293 deg s^{-1} case). We have a high initial force (preactivation) because of the release method. When the lever arms starts to move, the force rapidly abates until the time about $t = 150$ ms. The force bounces back reaching a second peak at around $t = 230$ ms whereafter it plummets. This case is interesting since the force is almost symmetrical around the middle point with a force increase again at the end due to the breaking phase.

From these Figures 1 - 3 it is evident that it is far from trivial to extract the force (or torque) and velocity data that can be compared with the Hill equation. For the pneumatic device the torque does reach a sort of a plateau after the initial acceleration. The question is of course whether this corresponds to the maximal attainable force at that velocity, or whether it is affected by neuro-muscular safety limitations. In the isokinetic case (Fig. 3) the velocity value is given, but how to pick the representative torque value? For a comparison of the methods discussed in section (section 2.1) we have drawn Fig. 4 which shows some of the $T-V$ curves for a single participant based on the aforementioned methods. The dotted line represents the theoretical Hill-curve (1) with the parameters $c = 2.5$ and (maximal angular velocity) $\omega_0 = 1000$ deg s^{-1}. In this instance the methods 1-3 seem to place the pneumatic device data quite close to the theoretical curve. It demonstrates the general rule that for the pneumatic device we have $\omega_{\mathrm{pp}} > \omega_{\mathrm{pt}} > \omega_{120}$ for a given resistance level.

In the same Fig. 4 we have also drawn the results using the weight stack machine (cross-symbols). The $(T_{\mathrm{pp}}, \omega_{\mathrm{pp}})$-data (peak power method, 3) is not too far off the other results while the $(T_{\mathrm{m}}, \omega_{\mathrm{m}})$-data (mean value method, 4) is significantly below the other curves. Generally the weight stack device data was difficult to analyse from the force-velocity point of view. This is likely to be an effect of the peculiar inertial dynamics of the device.

The concave-type curves produced by the isokinetic data was seen in most of our data and is related to the "plateau" that has been in found in many other investigations. Clearly it is impossible to combine the hyperbolic Hill-equation with a flat plateau. This raises the question whether it is an indication of the limitation of the Hill-equation (to be replaced by a "double-hyperbolic" relation or a lumped model) or whether it is due to some systematic measurement effect. The mean value method proposed by Rácz et al (2002) does not affect the plateau issue very much. Fig. 5 shows all torque-velocity pairs for the male group. Open symbols correspond the peak torque method, and filled symbols to the mean value method. Diamond stands for the isokinetic device data, and the circle stands for the pneumatic device data. The dotted line represents a Hill-curve included as a reference ($c = 2.5$, $\omega_0 = 1000$ deg s^{-1}). The data for the female group (Fig. 6) show a perhaps a slightly less pronounced "plateau"-phenomenon and apparently a smaller dispersion when compared with the male group data (Fig. 5). It is apparent from these figures that for many points it is more or less impossible to fit a meaningful Hill-curve. The curves that are too "high" up may indicicate that the isometric MVC torque T_0 has been underestimated and thus lead to an exaggeration of the ratio $\mu = T/T_0$, or that T_0 should be replaced by kT_0 in the Hill-equation with a correction factor $k > 1$. Indeed, say a 20% error in the estimate of the isometric MVC may have a signifcant effect on the fitting of the Hill-curve as shown by Fig. 7. The dashed line is fitted ($c = 1.5$, $\omega_0 = 1000$ deg s^{-1}) to the measured pneumatic data, whereas the solid line is fitted ($c = 3.0$, $\omega_0 = 1050$ deg s^{-1}) to the same data with the T/T_0 reduced by a factor of 0.8. This factor would be the needed correction if the MVC value T_0 were underestimated by 20%.

Three of the participants in the female group had MVC torque T_0 in the range of 141 - 153 Nm (measured with the pneumatic device; 136 - 163 Nm measured with the isokinetic device) and their results show some interesting features exemplified by Fig. 8. Here the pneumatic data has a sort of a plateau. In two of three of the cases the isokinetic data (according to maximum torque and fixed angle method) lies a bit above our standard Hill-curve as in Fig. 8. The low velocity/heavy load part of the pneumatic data may be affected by submaximal efforts (e.g. fatigue may be involved) as there is a considerable gap to the isokinetic data at $\omega \approx 73$ deg s^{-1}. In this case we can also observe that the mean value method puts the isokinetic data too low down.

Of the calculational methods the maximum power method seems most robust in case for the pneumatic device although the results do not differ much from those by the fixed angle and maximum torque method. The maximum power method is quite close to taking the point of maximum velocity since the resistance does not vary much during the critical part of the leg extensions. Fig. 8 shows typical power-angle relations for leg-extensions at increasing loads for the pneumatic device. From it we can see that the power-curve does not have a sharp maximum, but still the maximum regularily lies around the joint angle of 130° as can be seen from Tab. 2. In this table we have also calculated the average normalized torque T_{pp}/T_0 at the point of maximum power based on the data from he pneumatic device. For the male group we included only the "best" four of the tests since there obvious errors with the other four tests (as can be inferred from Fig. 5).

4 Conclusions

Based on the data presented in this study it still seems be difficult to obtain a "correct" way to construct a proper torque-velocity relationship. The data depends on a number of factors such as the dynamics of the device, the measurement protocol, the level of training of the participant, how the participant was strapped to the device, fatigue, and whether the performance was a successful one or not (e.g. submaximal). Furthermore there is the open issue whether one should use a "corrected" MVC-value kT_0 in the Hill-equation, and what would be the value of k, and might it vary from person to person. The good fit of the data to Hill-curves reported by Rácz et al (2002) may to a degree be due to data "pruning"; for every condition 10 performances were made of which the best five were selected and their average being taken as the final result. A further interesting point is that Rácz et al got best results not using the isokinetic setup but using a constant *acceleration* instead.

One explanation for the big variation seen in our data (Fig. 5) may be due to the lack of a similar "pruning". Thus from the male group about 4 of 8 results obtained from the pneumatic device seem to be compatible with the Hill-equation. The mean value method does not affect this matter to any great extent for the pneumatic data as can be seen from Fig. 5; for the isokinetic data the change is though somewhat more pronounced but it does not always entail a better fit to the Hill-equation. The effect of the mean value method could in some cases be due to some sort of an error compensation which e.g. corrects for an underestimated MVC isometric torque T_0. Still the biggest issue seems to be how to deterimine test conditions and methods which will provide maximally "robust" data for the construction of the torque-velocity relation. For instance, when employing the pneumatic device one might use fewer resistance levels (based on the isometric MVC) compensating with an increasing number of repetitions. Also it would be of interest in the future to investigate whether the torque-velocity relations established with the penumatic device can distinguish between athletes with predominantly fast and slow fibers along the lines of the results by Tihanyi et al (1982). In such a case the device would provide a convenient tool for monitoring muscle composition and the effects of exercise. Thus, if we want to follow up how a training scheme affects the velocity properties of the muscle one could determine how the angular velocity ω_{pp} and the normalized torque T_{pp}/T_0 at the maximum power changes over the course of a training period. It remains to be studied whether such a physiological effect can be separated from other training effects, such as a device related learning effect.

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5 Figure captions

FIG1 Typical graphs of force and joint angle (dotted curve) vs time, pneumatic device, and one MVC leg extension. Resistance set to 2 bars (lightest load used in the tests). The force peak marks the point where the lever arm hits the stopper.

FIG2 Typical graphs of force and joint angle (dotted curve) vs time, pneumatic device, and one MVC leg extension. Resistance set to 8 bars (heaviest load used in the tests).

FIG3 Typical graphs of force and joint angle (dotted curve) vs time, isokinetic device, and one MVC leg extension. Velocity preset to 293 deg s^{-1}, the fastest run used in the tests.

FIG4 Torque-velocity curves for one participant determined using different calculational methods (numbered 1, 2, 3, 4) and devices (circle symbol for the pneumatic device; triangle symbol for the isokinetic device; "plus" symbol for the weight stack machine). For the weight stack machine methods 1 and 2 did not extract any meaningful curve from the data. The dotted curve represents the theoretical Hill-curve (1) with parameters $c = 2.5$ and $\omega_0 = 1000$ deg s^{-1}.

FIG5 Torque (scaled)-velocity values for a group (men, $n = 8$), individual data shown. Circle for data obtained using the pneumatic device, diamond for isokinetic data. Torque and velocity computed for peak torque (open symbol) and as mean value(s) (filled symbol). The dotted line represents the Hill-curve for parameters $c = 2.5$ and $\omega_0 = 1000$ deg s^{-1}.

FIG6 Torque (scaled)-velocity values for a group (women, $n = 8$), individual data shown. Symbols the same as in Fig. 5. The pneumatic data does not include the 8 and 7 bar resistance extenssion since some of the women could not perform at these heavy loads.

FIG7 Example of how an error in the value of MVC maximum torque T_0 affects the Hill-curve fitting. Data from one of the test of the female group (who was able to perform also for the heaviest loads). Open circle corresponds to values measured with the pneumatic device, closed circles correspond to the same data but where where T_0 has been multiplied with a factor 1.25. Dotted line is the Hill-curve for $c = 1.5$ and $\omega_0 = 1000$ deg s^{-1}, while the solid line represents the Hill-curve for $c = 3.0$ and $\omega_0 = 1050$ deg s^{-1}. We have also included the isokinetic data (triangle symbols).

FIG8 Torque-velocity relations for a female participant with MVC $T_0 =$ 151 Nm (pneumatic device; 163 Nm with the isokinetic device). Circle stands for pneumatic device data and triangle for isokinetic device data. The dotted line represents the Hill-curve with $c = 2.5$ and $\omega_0 = 1000$ deg s^{-1}.

FIG9 Typical power-angle graph for the pneumatic device for a series of leg-extensions with increasing loads. The "wavy" fluctations of the curve is due to noise which is becomes amplified in differentiating the angular data when calculating the angular velocity $\omega = d\phi/dt$ in the expression for power $P = T \cdot \omega$. The angular velocity (and power) is positive for extension.

6 Table captions

TAB1 Time for reaching the fraction q of maximum velocity for constant load μ ($\mu = 1$ corresponds to isometric maximum) and the corresponding angle covered in that time. Case $c = 2.5$ and $\tau = 43$ ms. q is the fraction of the maximum velocity $(1-\mu)/(1+c\mu)$ attainable at the load μ according to the Hill-relation (2). The angles are based on the assumption that maximal velocity at zero load is given by 410 deg s$^{-1}/0.35 = 1171$ deg s^{-1}. Of course, angles over 90° are unrealistic, but they are included because the table can be used for other values of τ and ω_0 by scaling.

TAB2 Averages and standard deviations of T_{pp}/T_0, ω_{pp} and ϕ_{pp} for (normalized) torque and the angular velocity at the point (ϕ_{pp}) of maximum power as computed from the pneumatic device data. For the male group we have selected only four of the "best" results of eight in the group. If we also take into account the gravity effect (see section 2.2.3) this would add about 10% to the ratio T_{pp}/T_0.

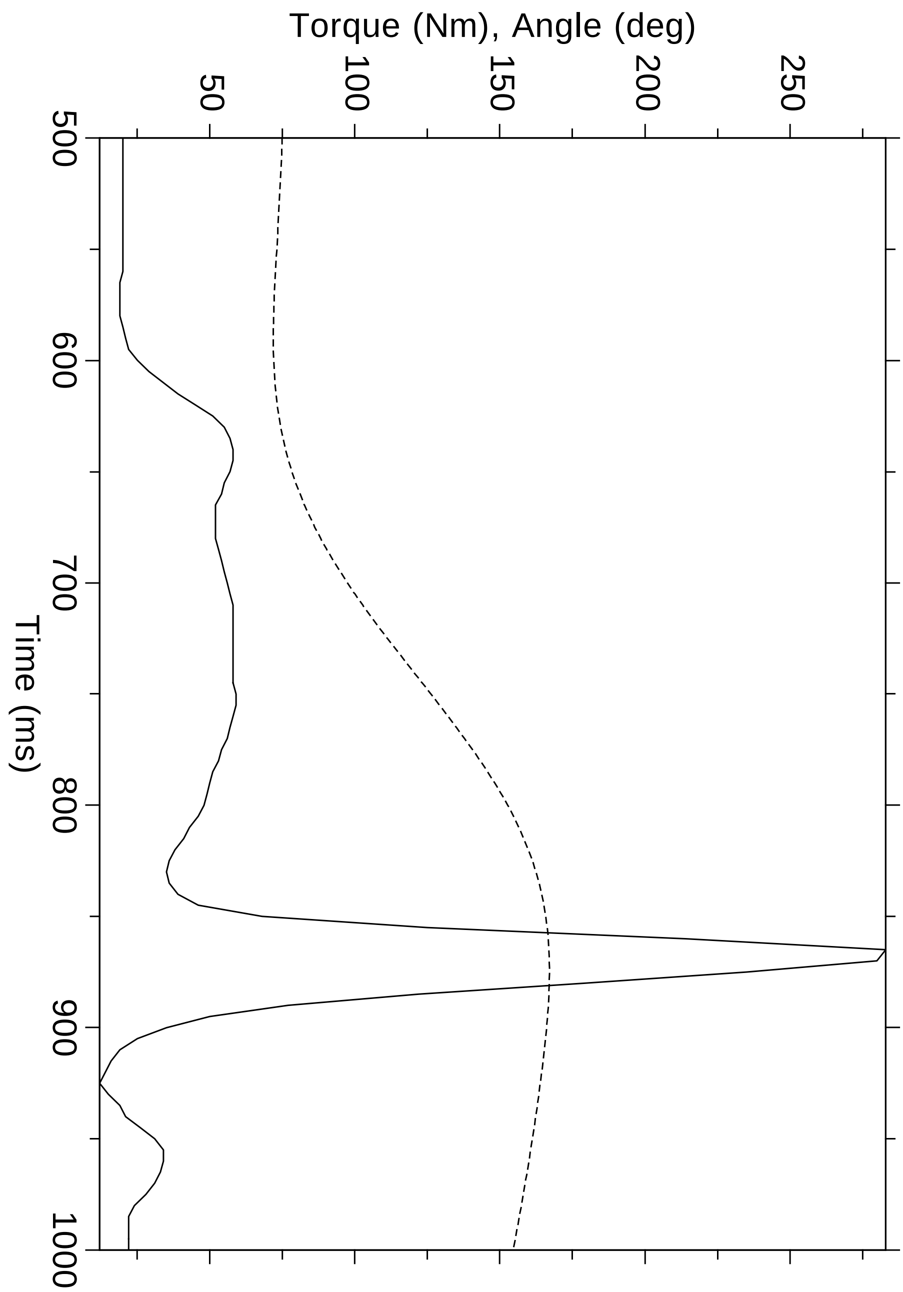

Figure 1 Typical graphs of force and joint angle (dotted curve) vs time, pneumatic device, and one MVC leg extension. Resistance set to 2 bars (lightest load used in the tests). The force peak marks the point where the lever arm hits the stopper.

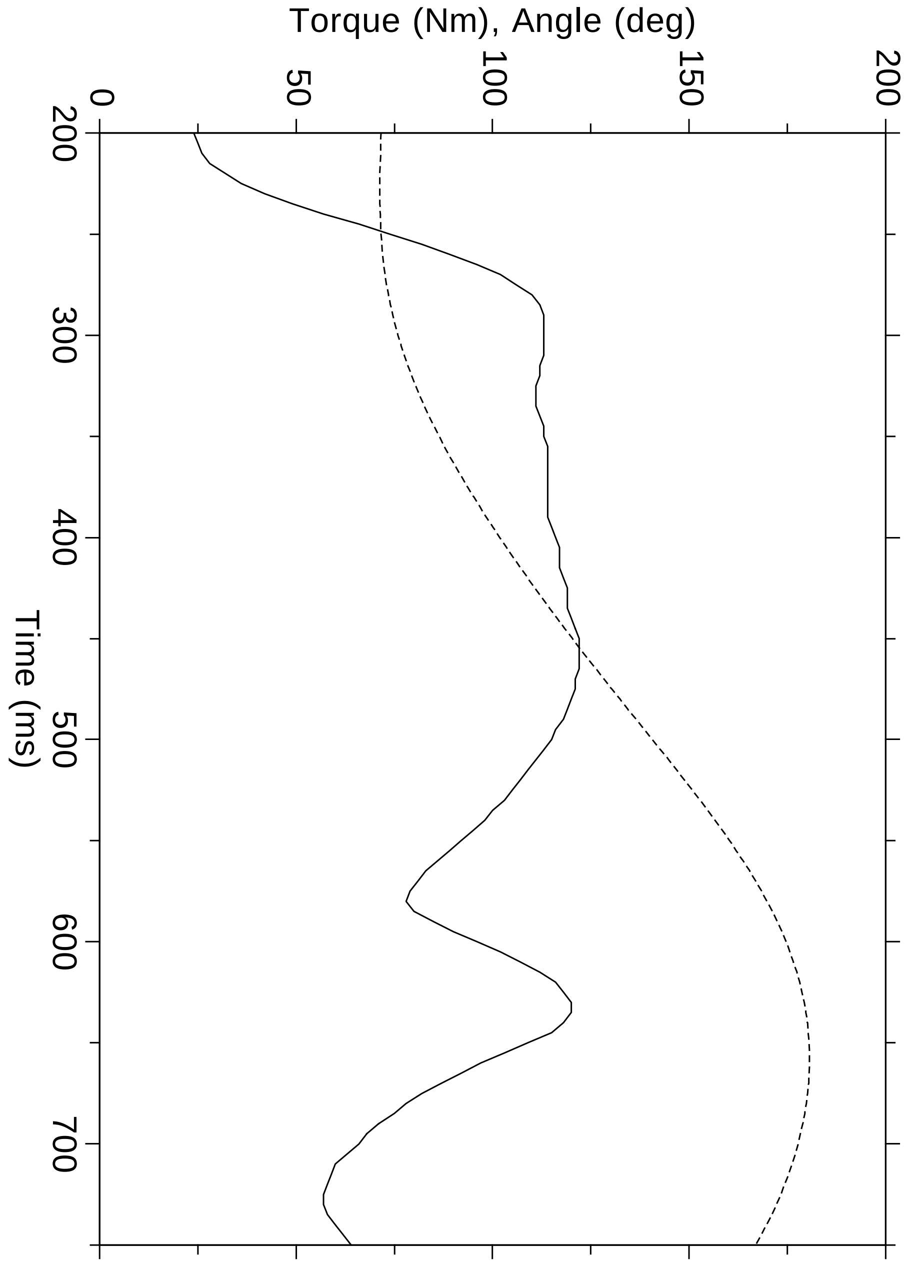

Figure 2 Typical graphs of force and joint angle (dotted curve) vs time, pneumatic device, and one MVC leg extension. Resistance set to 8 bars (heaviest load used in the tests).

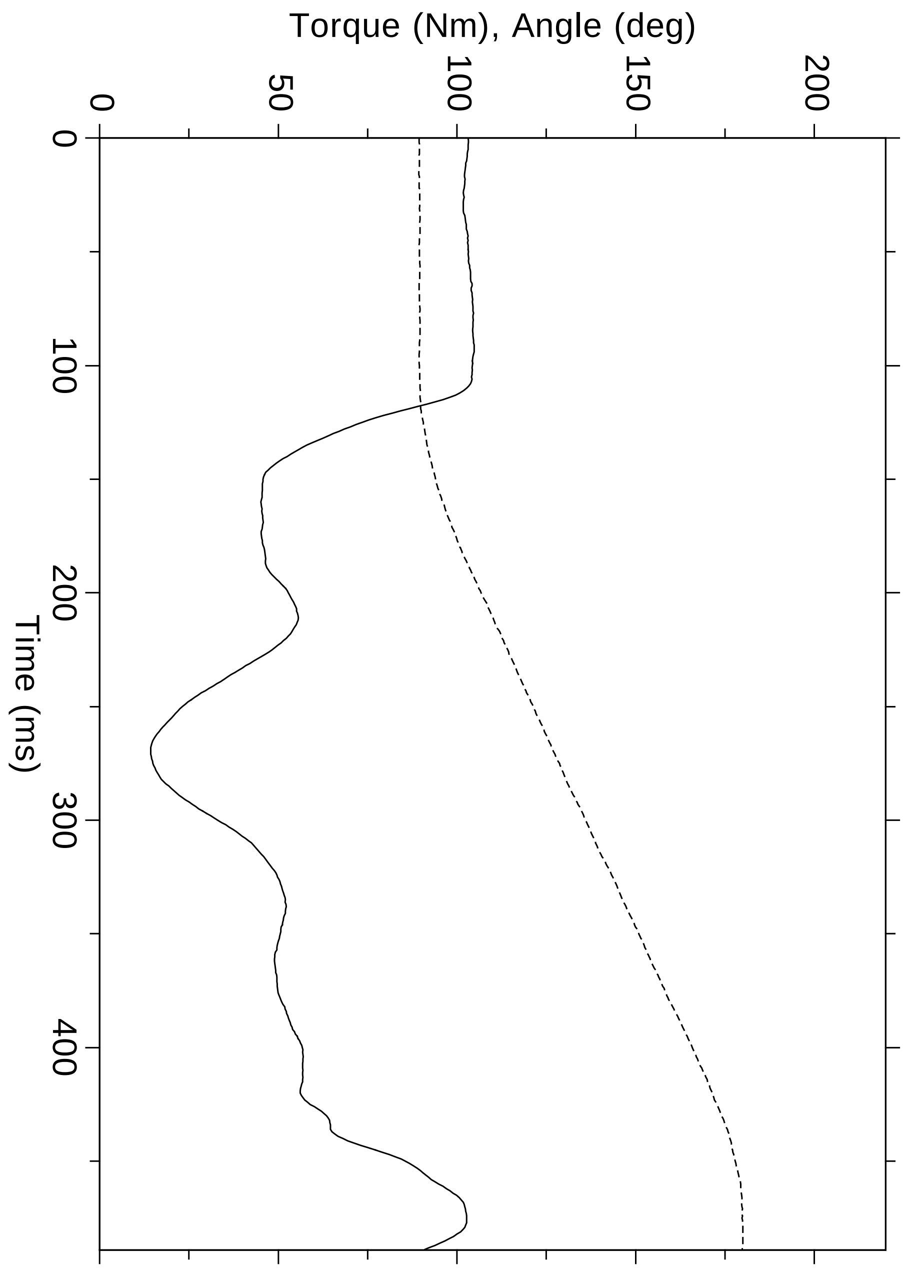

Figure 3 Typical graphs of force and joint angle (dotted curve) vs time, isokinetic device, and one MVC leg extension. Velocity preset to 293 deg s^{-1}, the fastest run used in the isokinetic tests.

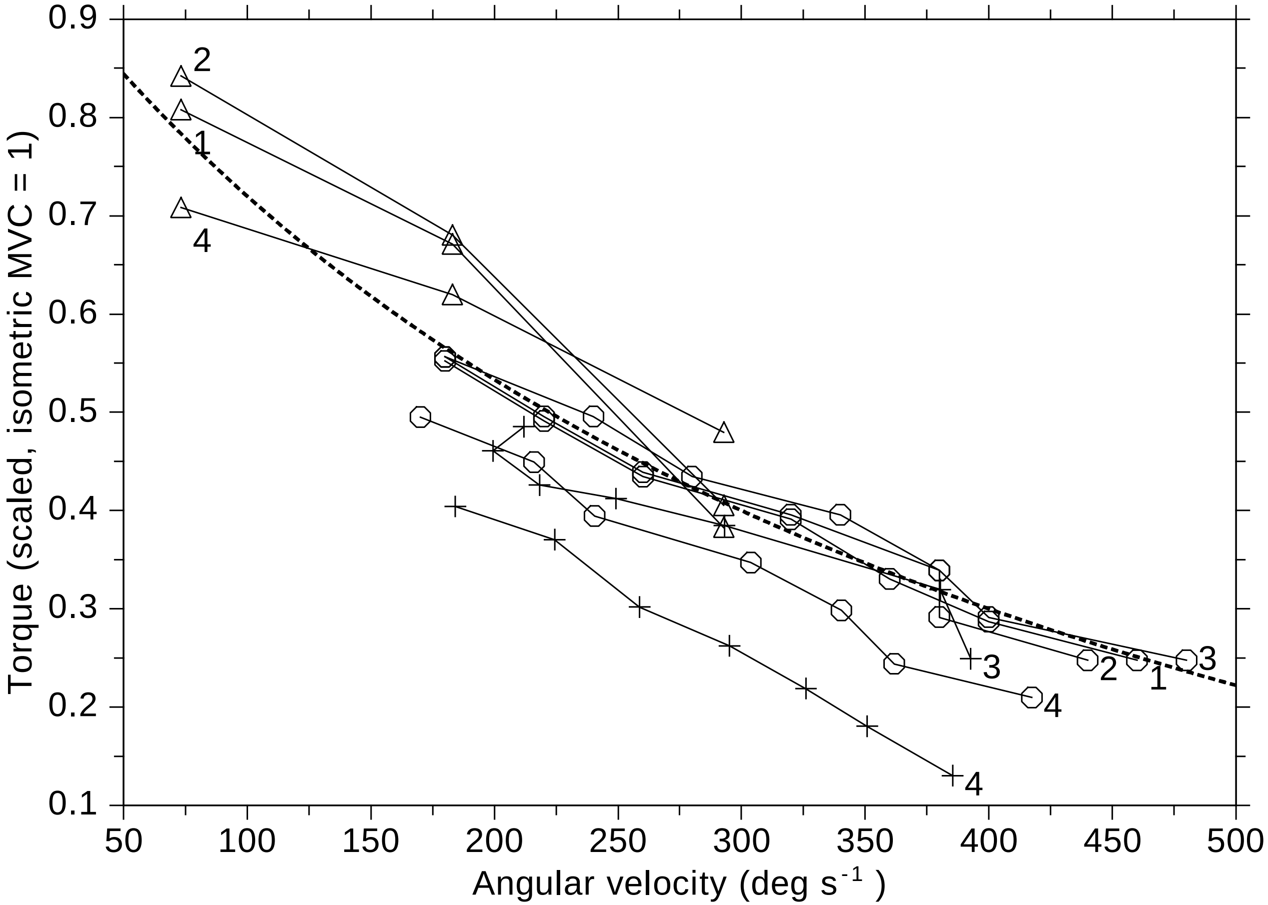

Figure 4 Torque-velocity curves for one participant determined using different calculational methods and devices.

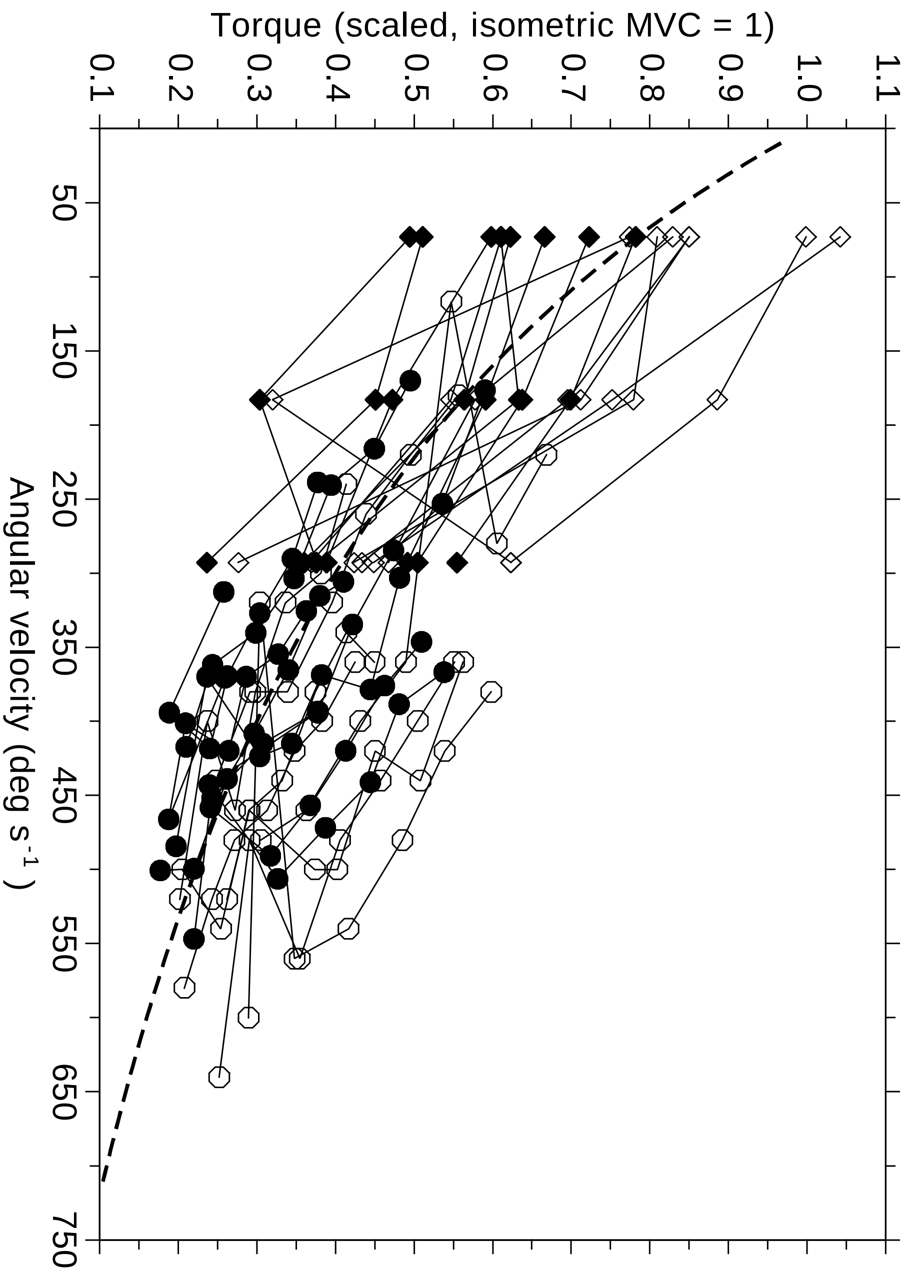

Figure 5 Torque (scaled)-velocity values for a group (men, $n = 8$). Circle for data obtained using the pneumatic device, diamond symbol for the isokinetic device data.

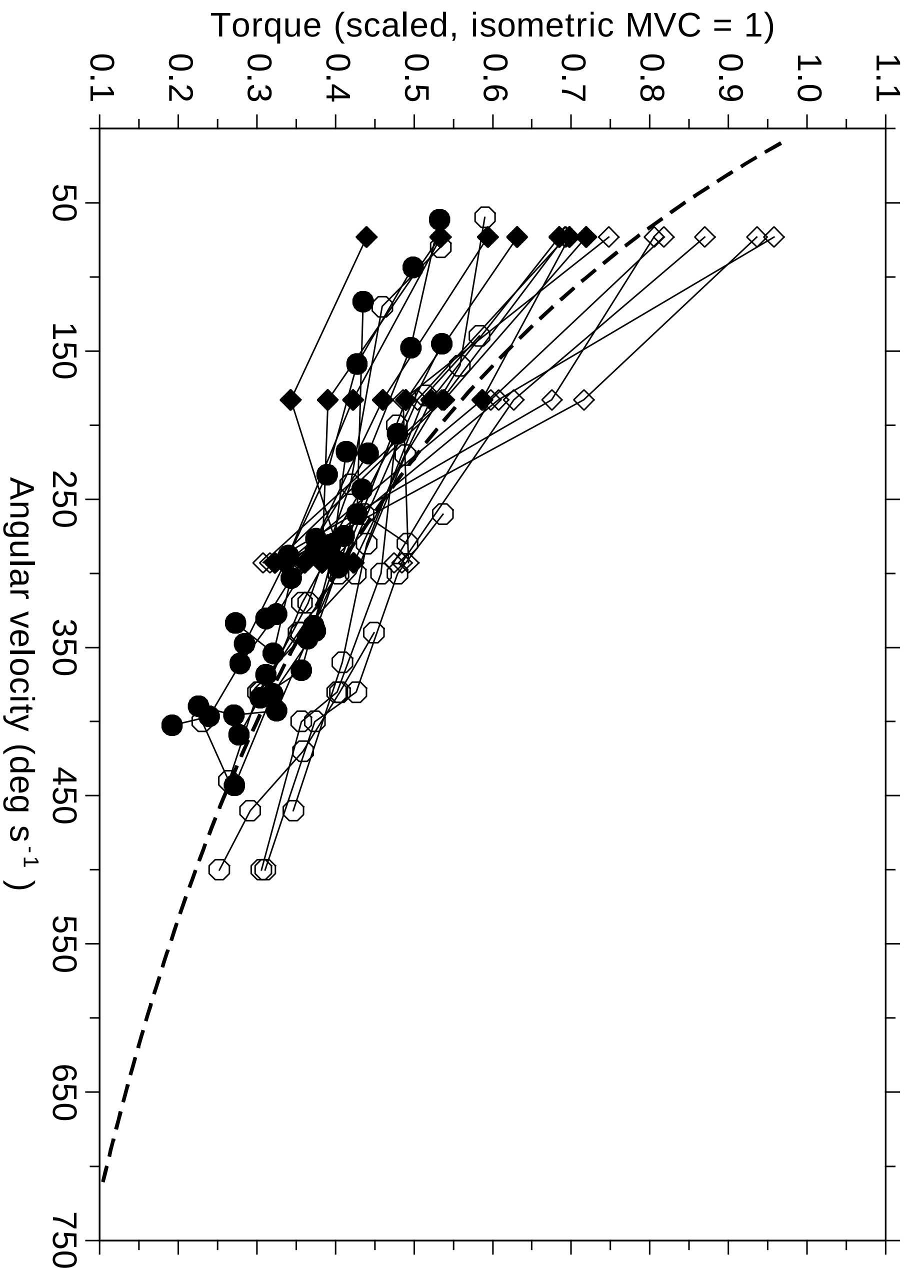

Figure 6 Torque (scaled)-velocity values for a group (women, $n = 8$). Circle for data obtained using the pneumatic device, triangle for data obtained with the isokinetic device.

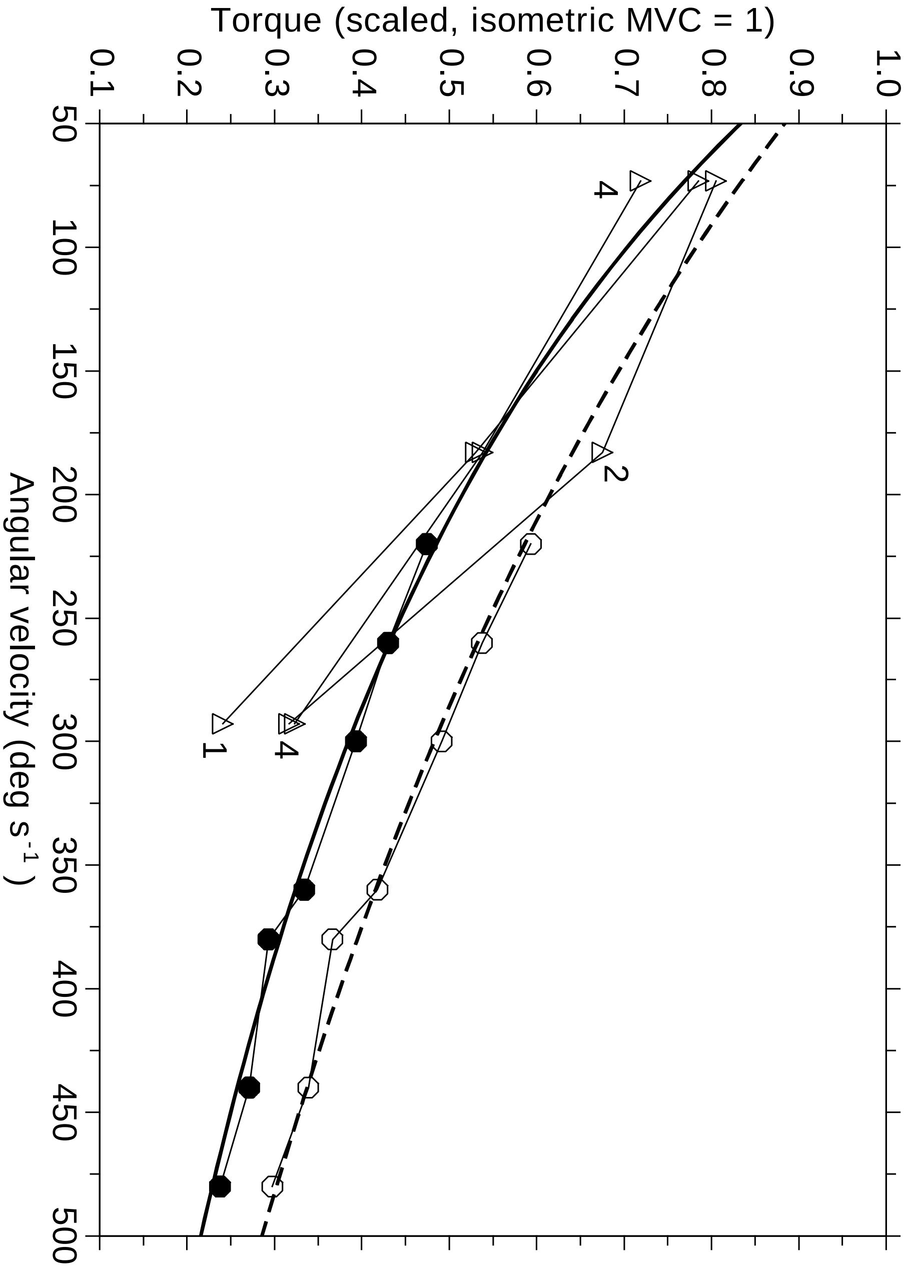

Figure 7 Example of how a an error in the value of MVC maximum torque T_0 affects the Hill-curve fitting. Data from one of the test of the female group (who was able to perform also for the heaviest loads). Open circle corresponds to values measured with the pneumatic device, closed circles correspond to the same data but with T_0 multiplied with a factor 1.25.

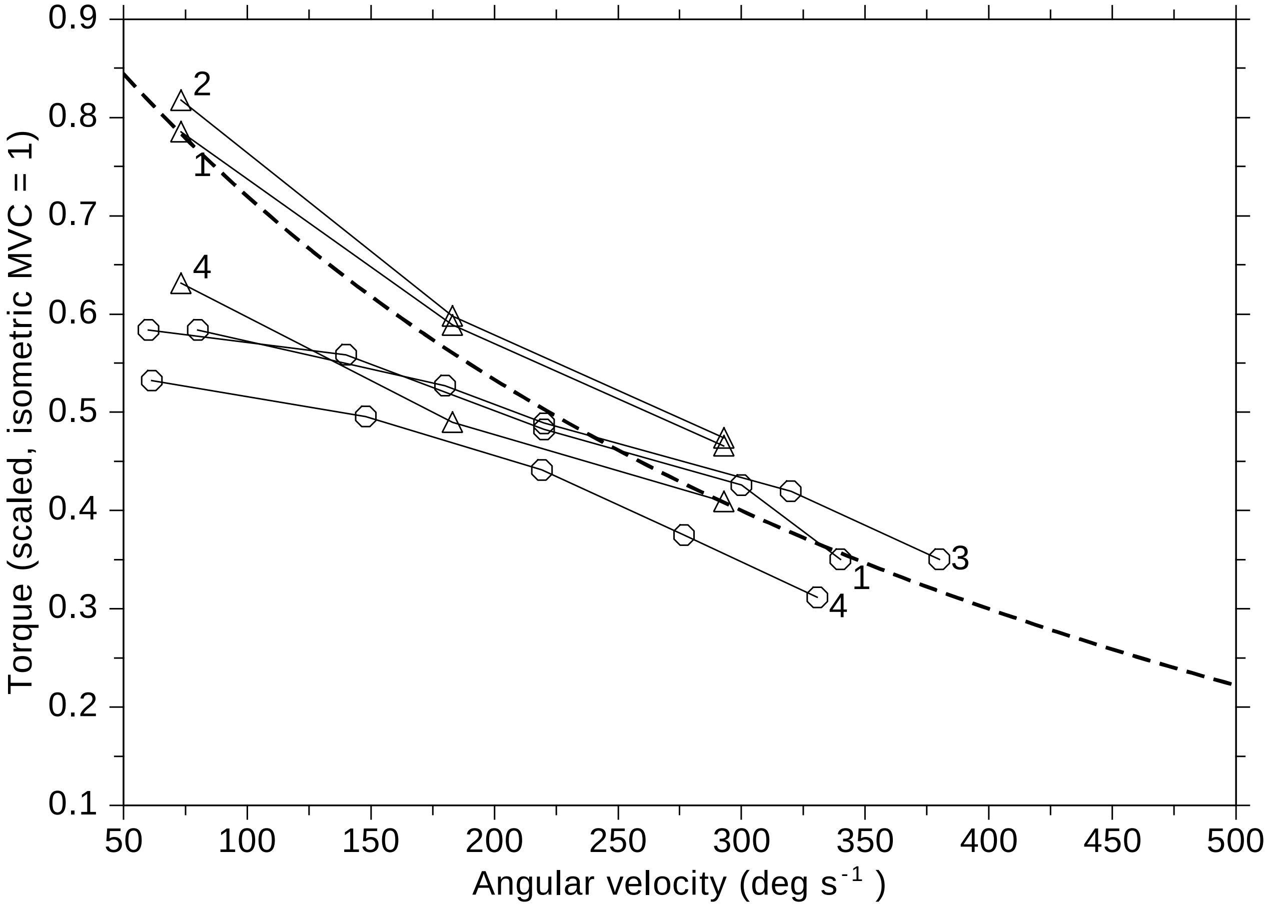

Figure 8 Torque-velocity relations for a female participant with isometric MVC $T_0 = 153$ Nm (pneumatic device).

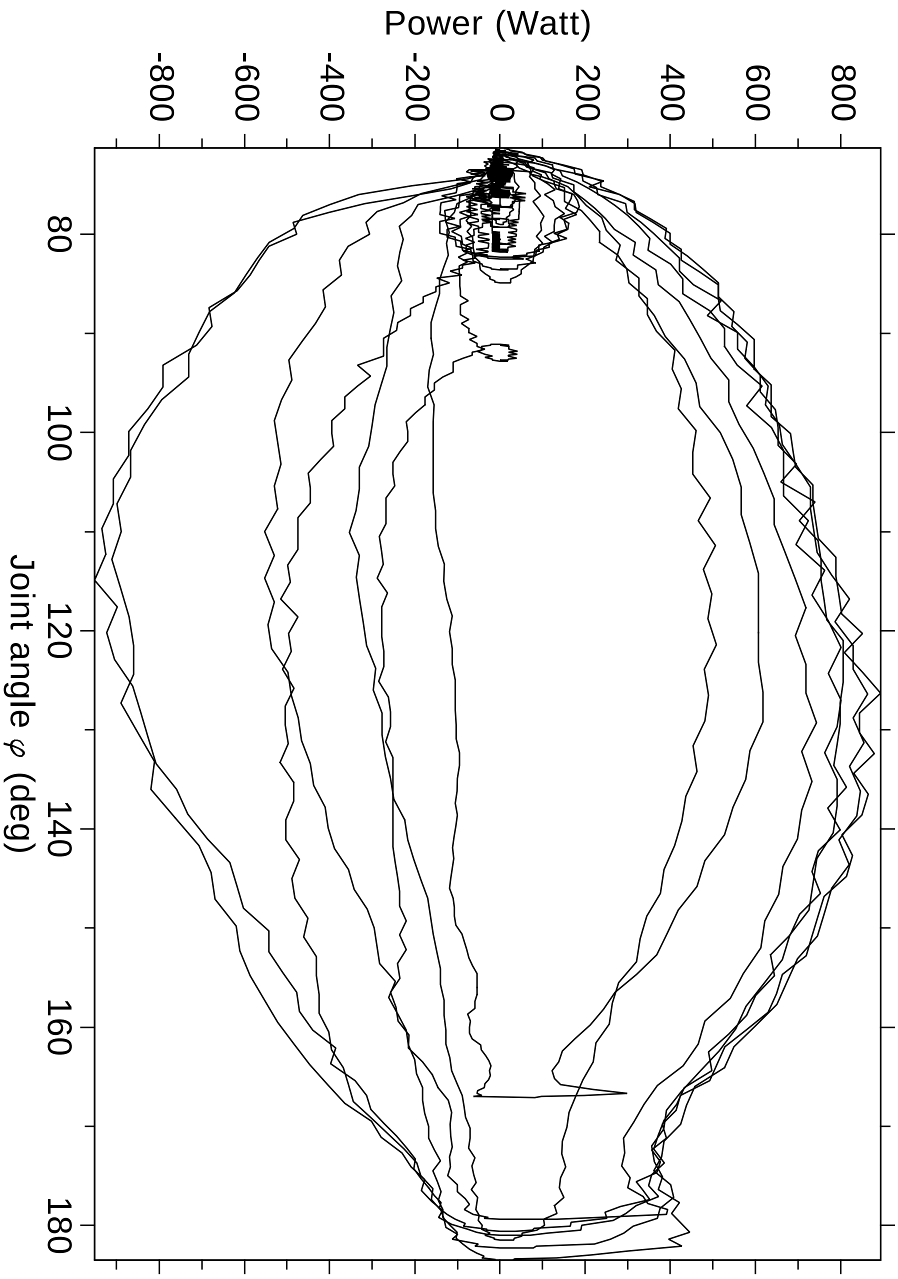

Figure 9 Typical power-angle graph for the pneumatic device for a series of leg-extensions with increasing loads.

q (%)	t (ms) and $\phi(t)$				
	$\mu = 0$	$\mu = 0.1$	$\mu = 0.2$	$\mu = 0.35$	$\mu = 0.5$
50	50 18°	35 9°	27 5°	20 2°	15 1°
60	73 33°	51 16°	38 9°	27 4°	21 2°
70	105 57°	72 28°	53 15°	37 7°	28 3°
80	154 101°	104 48°	76 26°	52 11°	39 5°
90	247 193°	164 91°	118 48°	80 21°	58 10°
95	345 301°	227 140°	162 73°	108 31°	78 14°

Table 1 Time t for reaching the fraction q of maximum velocity for constant load μ ($\mu = 1$ corresponds to isometric maximum) and the corresponding angle $\phi(t)$ covered in that time t. Case $c = 2.5$ and $\tau = 43$ ms.

	T_{pp}/T_0	ω_{pp} (deg s^{-1})	ϕ_{pp} (deg)
Women	0.38 ± 0.04	397 ± 42	128 ± 3
Men	0.37 ± 0.07	420 ± 57	132 ± 6

Table 2 Averages of T_{pp}/T_0, ω_{pp} and ϕ_{pp} for (normalized) torque and the angular velocity at the point (ϕ_{pp}) of maximum power as computed from the data. For the male group we have selected only four of the "best" results of eight in the group.