ASSESSMENT OF FUNCTIONAL SERIES-ELASTIC STIFFNESS OF THE
HUMAN PLANTAR- AND DORSI-FLEXORS IN VIVO
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INTRODUCTION
The series-elastic stiffness of muscles (SES), which is dominated by the elasticity of tendinous structures, has a significant influence on both the control and the economy of movement (Rack et al. 1983; van Ingen Schenau et al. 1997). However, for making a quantitative evaluation of the functional significance of SES reliable quantitative measures of SES in humans \textit{in vivo} have to be available.

Ultrasoundography or rather a combination of ultrasonography, MRI and measurement of external joint moment has been used rather intensively over the last five years to study the mechanical properties of human tendons and aponeuroses in vivo. Several studies have provided interesting knowledge about basic series-elastic connective tissue properties and the interaction between muscle fascicles, tendon and aponeurosis (Maganaris and Paul 1999; Maganaris and Paul 2000b; Muramatsu et al. 2001). However, the methodology has significant limitations e.g. the length changes measured on the ultrasound pictures only represent local deformation of connective tissue (i.e. the measured deformations correspond to a one-dimensional measure on a thee dimensional structure) and since the corresponding force essentially is not known, because the internal force distribution in the muscle-tendon unit is not known, the relationship between force and deformation can be questioned. Additionally, the dimensions of the connective tissue (when measured) are only partially measured. Therefore it may seem questionable to interpret the results quantitatively and in a functional sense.

An alternative method which can be used to measure SES in vivo is the so called ‘quick release’ (QR) method where active muscles are shortened very fast with minimum muscle fiber shortening, and in this situation the relationship between the muscle-tendon length change and the decrease in muscle force describes the mechanical properties of the series-elastic component of the active muscle(s) involved (Hof 1998; Pousson et al. 1990). However, in spite of the potential for providing important information concerning muscle function \textit{in vivo} in humans only very few researchers have so far been working with this technique in vivo in humans.

The purpose of this study was to quantify human SES \textit{in vivo} in plantar-flexor and dorsi-flexor muscles with the quick release method.

MATERIAL AND METHODS
We have developed a computer controlled high-pressure hydraulic device (Voigt et al. 1999) that can produce angular rotations between 15–20 rad s\(^{-1}\) in a wide range of human joints for application of the QR-method.

\textbf{Figure 1}
A diagram describing the foot-adapter and the forces and accelerations measured to determine the ankle joint moment. The moments around the centre of rotation (COR) was calculated by multiplying $F_c$ with the moment arm $L$, and $F_a$ and $F_b$ with the moment arm $H$ and add them together. The accelerations $A_a$ and $A_b$ were measured with accelerometers. The angular acceleration was calculated using these two linear accelerations and the geometry. The CORs of the ankle joint and the actuator were carefully aligned and the foot firmly attached with large rigid cable ties.
The local ethical committee approved safety and procedures. In the present study SES was measured in healthy subjects in plantar-flexors (N=10) and dorsi-flexors (N=8) with QR. The releases were applied over a range of 30 degrees and to minimize the contribution from passive joint stiffness the releases were initiated at 10 degrees dorsi-flexion ending at 20 degrees plantar-flexion. The subjects were placed comfortably in a chair with the right knee joint in approximately 20 degrees flexion and the hip joint in approximately 80 degrees flexion. The foot was firmly attached to a special adapter instrumented with load cells (Kistler, Slimline) and accelerometers (Kistler, Piezotron) (see fig.1). The center of rotation (COR) of the ankle joint was carefully aligned with the COR of the hydraulic actuator. To isolate muscle action before the releases to either tibialis anterior (TA) or to triceps surae (TRS) static muscle action was generated by electrical stimulation (1 s percutaneous stimulation at 100Hz (Axon Isolator-11, Axon Instruments)). Releases were also performed after voluntary generation of static muscle action in either dorsi- or plantar flexion. Correction for passive joint stiffness, inertia effects and muscle fiber shortening was applied using a strategy modified after the methods described by Hof (1998). Each test consisted of twenty releases with different initial levels of static muscle action. After correction the release curves were shifted according to their different starting point at the series-elastic release curve due to the different initial levels of static muscle action. Finally, the shifted curves were averaged giving a final representation of the series-elastic release curve. The SES was clearly dependent on the force (moment) level and for comparison between plantar- and dorsi-flexors SES was determined at a tendon stress of about 30 MPa during electric stimulation, using data on tendon cross sectional area from the literature.

RESULTS
The main results are presented in table 1. For the dorsi-flexors the maximal electrically activated moment was 48% smaller than the maximal voluntary moment (p<0.05). For the plantar-flexors however the maximal electrically activated moment was 19% larger than the maximal voluntary moment (p<0.05).

<table>
<thead>
<tr>
<th>Electrical stimulation</th>
<th>Max moment (Nm)</th>
<th>SES (Nm rad-1)</th>
<th>Youngs modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA</td>
<td>34 (16)*</td>
<td>127 (31)*</td>
<td>0.77</td>
</tr>
<tr>
<td>TRS</td>
<td>129 (25)†</td>
<td>529 (125)</td>
<td>1.02</td>
</tr>
</tbody>
</table>

Voluntary contraction

| DORSI-FLEXORS          | 66 (17)*        | 186 (45)*       | -                    |
| PLANTAR-FLEXORS        | 108 (36)†       | 506 (72)        | 0.97                 |

SES of TA (electrical stimulation) was significantly lower (68%, p<0.05) than SES of the voluntary activated dorsi-flexors. SES of TRS during electrical activation was not significantly different from SES obtained during voluntary activation. Youngs modulus for the series-elastic tissue (assuming that this tissue corresponds to the tendinous structures) in TA and TRS was estimated using information about tendon moment arm (a_M), cross-sectional area (PCA_T) and tendon length (l_0) from the literature: for TA: a_M = 0.036 m, PCA_T = 20.3 mm² and l_0 = 0.162 m and for TRS: a_M = 0.051 m, PCA_T = 61.0 mm² and l_0 = 0.303 m.

DISCUSSION
With the setup and the methodology we have developed it has been possible to quantify functional SES non-invasively in vivo in humans in dorsi-flexor and plantar-flexor muscles/muscle groups with reasonable accuracy. We believe that this methodology based on QR can be used to quantify SES over a wider range of joints. However, refinements in both the measurement and in the signal processing procedures can still improve the methodology. Additionally, a combination of the QR-technique with the information obtained from the imaging methods may further improve the accuracy of the information that can be obtained about in vivo SES.
The stiffness difference measured between electrical (TA) and voluntary activation (dorsi-flexors) (VOL>EL, p<0.05) indicates that voluntary dorsi-flexion is generated by a balanced activation of a synergy, composed of TA (dorsi-flexion/inversion) and extensor digitorum and extensor hallucis longus (dorsi-flexion/eversion). The SES measured by QR during the voluntary activation therefore corresponds to the functional elasticity of the active synergy. In TRS there was no significant stiffness difference between electrical and voluntary activation indicating that the deep plantar-flexors were not activated significantly during the voluntary action.

Our results seem to support previous observations concerning SES in plantar- and dorsi-flexors. The SES is dominated by the elasticity of tendinous structures and the average value for Youngs modulus of the free parts of human tendons measured in vitro is 1.2 MPa (Voigt et al. 1995). Maganaris et al. (2000b) came very close to this value for the free distal tendon of TA using the method based on ultrasound. In the present study Youngs modulus for TA was estimated to be 0.77 MPa. This value may seem rather low, however the functional SES is the combined stiffness of the free tendon + aponeurosis. In TA the aponeurosis is more compliant than the free part of the tendon (Maganaris and Paul 2000a) and the ratio between the strain of the free tendon alone (3.1%) and the accumulated strain of the free tendon + aponeurosis (4.8%) is 0.65. In the present study the corresponding ratio can be determined as the ratio between the Youngs moduli of TA tendon + aponeurosis measured by QR (0.77) and the free tendon alone (1.2 GPa) and this ratio is 0.64. These ratios are in close agreement and therefore our measurements with the QR method seem to support the previous observation of a stiffness difference between the aponeurosis and the free tendon of TA. In triceps surae Youngs modulus of the free part of the tendon in vivo has been determined to be 1.47 GPa by the ultrasound based method (Magnusson et al. 2001). The value we obtained was about 38% lower (1.02 GPa) indicating that also the aponeuroses of the triceps surae muscle complex have a lower combined stiffness than the Achilles tendon alone.

ACKNOWLEDGEMENTS
We would like to thank Francisco Sepulveda for assisting with the signal processing for the correction methods. The Danish National Research Foundation supported this work.

REFERENCES