Tendon elongation influences the amplitude of interpolated doublet forces in the assessment of activation in elderly men

Christopher I. Morse,1 Jeanette M. Thom,1 Karen M. Birch,2 and Marco V. Narici1

1Institute for Biophysical and Clinical Research into Human Movement (IRM), Manchester Metropolitan University, Alsager, Cheshire; and 2University of Leeds

Institute of Sport and Exercise Science, University of Leeds, Leeds, United Kingdom

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Morse, Christopher I., Jeanette M. Thom, Karen M. Birch, and Marco V. Narici. Tendon elongation influences the amplitude of interpolated doublet forces in the assessment of activation in elderly men. J Appl Physiol 98: 221–226, 2005. First published September 3, 2004; doi:10.1152/japplphysiol.00774.2004.—This study investigated the influence of tendon elongation (TE) on postcontraction doublet (PCD) torque in the assessment of activation in the plantar flexors of nine elderly men (EM, age 73.7 ± 3.6 yr) and nine young men (YM, age 24.7 ± 4.7 yr). Plantar flexion maximal voluntary contractions (MVC) and activation were assessed at ankle joint angles of −20° (dorsiflexion), 0°, and 20° (plantar flexion). Across the ankle joint angles tested, compared with YM, the EM had a 36–49% lower plantar flexion MVC (P < 0.01), TE was greater by 25–31% (P < 0.01), and electromechanical delay was 65–108% greater (P < 0.01). Activation (PCD torque to interpolated doublet torque) was 15% lower in EM compared with YM at −20° (P < 0.05), but no different at 0 and 20°. In the EM, PCD torque relative to MVC torque was significantly lower at 20° compared with 0° (P < 0.05). Electromechanical delay was positively correlated with TE (R2 = 0.489, P < 0.01). In conclusion, this investigation demonstrates that, although a negative association exists between TE and PCD torque, the consequence of a greater TE on the estimation of activation in EM is negligible. This is due to a greater influence of ankle joint angle on the occlusion of a superimposed doublet, which counteracts the lesser influence of joint angle on TE and PCD torque. However, a greater TE in EM was found to significantly increase electromechanical delay, which is expected to influence the time needed for postural readjustments.

Conversely, complete activation has also been reported for the same muscles of the elderly (10, 24) and also in the plantar flexor and dorsiflexors (4, 31). Some of the variability in activation capacity reported by these studies appears to be due to methodological differences. For example, the studies reporting an activation deficit in the elderly employed multiple twitch trains to interpolate a maximal voluntary contraction (MVC) (5, 28, 29, 33), whereas most of the studies reporting complete activation in the elderly relied on single supramaximal twitch interpolation or a modified double twitch technique (4, 10, 24, 25, 31).

The accuracy of the interpolated twitch technique (ITT) (the ratio of the superimposed twitch torque to the resting twitch torque) has been previously investigated (1) and has been shown to overestimate activation compared with tetanic stimuli (2). In contrast, the use of double twitch interpolation has yielded estimates of activation similar to those obtained from the interpolation of a pulse train (2). One limitation of the ITT is the possible underestimation of activation as a result both of system compliance and of passive stretch reducing the resting twitch torque (7, 15, 27). This underestimation is particularly relevant in assessing activation in older populations because tendon compliance is known to be increased in the elderly (17, 32). Also, because twitches evoked at rest will generate small forces, they are expected to occur in the more compliant region of the tendon force-elongation relationship (18, 19) and therefore contribute to an underestimation of activation when this is expressed as the ratio of superimposed twitch torque to resting twitch torque. In addition, in some previous investigations (5, 10, 12), activation has been assessed at a short muscle length, likely resulting in tendon slack (22) and thus an understimation of activation capacity in the elderly. One could hypothesize, therefore, that a greater tendon elongation (TE) would contribute to a reduction in twitch doublet amplitude, particularly at short muscle length at which considerable slack is expected, and hence influence the assessment of activation.

One way in which activation can be assessed without the influence of TE is by using a ratio of the interpolated to voluntary torque, termed the central activation ratio (CAR) (11). However, the CAR has been shown to overestimate activation compared with the ITT technique, particularly when twitches are used as opposed to tetanic stimuli (2).

Hence, the aim of the present investigation was to determine the influence of TE on 1) the magnitude of the resting doublet in the plantar flexion of elderly men (EM) and 2) the assessment...
oment of activation based on ITT, measured at a stretched, shortened, and neutral muscle length, and to compare this to the CAR, which is independent of changes in TE.

MATERIALS AND METHODS

Nine healthy young men [YM, age 24.7 ± 4.7 yr (range 19–35), height 179.3 ± 7.8 cm, mass 76.9 ± 12.4 kg, mean ± SD] and nine healthy EM [age 73.7 ± 3.6 yr (range 70–82 yr), height 170.4 ± 4.5 cm, mass 77.5 ± 8.1 kg] volunteered to participate in this study. Elderly subjects were all medically screened before inclusion to exclude known cardiovascular, muscular, neurological, and inflammatory diseases and were all community dwelling and lived independently. Both young and elderly individuals were physically active but not participating in a structured training regime. All procedures were approved by the Ethics Committee of Manchester Metropolitan University, and prior informed consent was obtained from each subject. Subjects were familiarized with all proceedings in a separate session before data collection.

**Strength measurements.** Isometric plantar flexion MVC torque was recorded with subjects in a prone position, with the left foot attached to the foot adapter of an isokinetic dynamometer (Cybex Norm, Ronkonkoma, NY). Torque was displayed via an analog-to-digital converter and analyzed with the accompanying software (Acknowledge, Biopac Systems, Santa Barbara, CA). MVC was determined as the peak torque produced during a voluntary effort. Subjects were strapped securely about the hip to minimize leg movement during maximal plantar flexions. Subjects were positioned with the knee at full extension and the lateral malleoli aligned with the axis of rotation identified on the dynamometer. The foot was secured tightly to the footplate to minimize heel displacement during contractions, and the subjects performed three submaximal isokinetic contractions as a warm-up throughout their full range of movement. For the assessment of strength, two MVCs were performed at ankle angles of −20°, 0, and 20° (where 0° is with the foot at right angles to the tibia and −20° was in dorsiflexion). MVC attempts were performed in a randomized order, with at least 2 min separating every contraction. Supramaximal doublets were imposed on the second MVC attempt. Throughout attempts to perform MVC, subjects were given verbal encouragement. All subjects were comfortable and able to produce torque throughout the required range of movement.

**TE.** TE was measured at each of the three ankle joint angles at which MVC was assessed (−20°, 0 and 20°). Participants were positioned as described above for strength testing. The myotendinous junction (MTJ) of the lateral head of the gastrocnemius was located by use of sagittal plane ultrasonography. A 7.5-MHz linear array B-mode probe (HDI-3000, ATL, Bothell) was used to identify the MTJ as the convergence of the deep and superficial aponereoses (18). Before strength testing, subjects were instructed to perform isometric ramp plantar flexion contractions increasing in force to maximum over 4 s. Three conditioning ramp MVCs were performed before two test contractions at each ankle joint angle. TE was measured by tracking the proximal displacement of the gastrocnemius lateralis MTJ during an isometric plantar flexion contraction, by use of ultrasound (Fig. 1). The movement of the MTJ was recorded on video at 25 Hz during the test contractions and acquired at 25 Hz with a capture card (micro-Motion, DC30 board, Pinnacle Systems, Braunschweig, Germany) fitted in a Macintosh G4 computer and analyzed offline with image analysis software (NIH image, version 1.61/ppc, National Institutes of Health, Bethesda, MD). TE was determined as the proximal distance moved by the MTJ from rest to 25 N·m relative to an external marker secured on the dermal surface (19). To obtain a direct comparison of TE without the influence of greater strength in the young subjects, an absolute plantar flexion torque of 25 N·m was chosen to assess displacement of the MTJ, hence TE. This joint torque was selected for the analysis of TE because it corresponded with the maximum torque that could be generated by the weakest elderly individual at +20°. Furthermore, this torque was representative of the postcontraction doublet (PCD) torque elicited by stimulation. To determine the possible influence of resting tendon length, tendon strain was calculated by normalizing TE to Achilles tendon length.

**Activation.** To evaluate the ability of subjects to fully activate the plantar flexors during static contractions, three supramaximal doublets were applied percutaneously (DSV Digitimer Stimulator, Digitimer, Welwyn Garden City, UK) at each angle with use of rubber stimulation pads (76 mm × 127 mm, and 38 mm × 89 mm, Versastim, Conmed). The anode was placed distal to the popliteal crease and the cathode over the distal MTJ of the soleus. The supramaximal doublet amplitude was determined before interpolation by administering twitches of progressively increasing stimulation strength. Twitches were administered with the subjects in a relaxed state at 0° starting from 100 mA and increasing by increments of 50–100 mA until no further increase in twitch torque was observed with a further 50 mA increase in stimulation strength. Although tetanic stimulation provides the most accurate means of assessment (11), doublets were chosen because they have been shown to be as accurate as tetanus when ITT is used (2) and have previously been employed to assess activation in elderly groups (4, 10, 12). Doublets may also reduce the degree of discomfort felt by the participants compared with pulse trains (20); this is of relevance because pain would inhibit the development of MVC in more sensitive individuals.

Three doublets were applied to assess activation; the first two doublets (pulse width of 50 μs, intertwitch interval 10 ms) were applied during MVC and a further doublet applied on relaxation (PCD), each separated by 1.5 s. The first doublet was delivered manually during the plateau phase of an MVC attempt, and the subjects were encouraged to continue contracting maximally until the

![Fig. 1. Measurement of tendon elongation. Sagittal plane ultrasonography was used to capture proximal displacement of the gastrocnemius myotendinous junction relative to an external marker (broken line) from rest (A) to 25 N·m of plantar flexion (B). Elderly men (EM) demonstrated greater values of tendon elongation than young men (YM); both groups showed greater elongation when contractions were performed in a plantar-flexed position.](http://jap.physiology.org/DownloadedFrom/10.1152/jappl.00578.2004)
Table 1. Strength, tendon, and neural characteristics of the plantar flexors recorded at 3 ankle joint angles in YM and EM

<table>
<thead>
<tr>
<th>Ankle Joint Angle</th>
<th>−20°</th>
<th>0°</th>
<th>+20°</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF MVC YM, N·m</td>
<td>176.5 ± 37.5</td>
<td>126.8 ± 27.0</td>
<td>67.4 ± 21.4</td>
</tr>
<tr>
<td>PF MVC EM, N·m</td>
<td>199.4 ± 35.3</td>
<td>80.9 ± 13.7</td>
<td>34.7 ± 8.2</td>
</tr>
<tr>
<td>TE25 N, cm</td>
<td>0.34 ± 0.09</td>
<td>0.49 ± 0.13</td>
<td>0.71 ± 0.15</td>
</tr>
<tr>
<td>EM. means</td>
<td>0.45 ± 0.10*</td>
<td>0.72 ± 0.10†</td>
<td>0.96 ± 0.19†</td>
</tr>
<tr>
<td>Resting tendon length YM, cm</td>
<td>10.8 ± 0.7</td>
<td>10.7 ± 1.5</td>
<td>9.1 ± 0.6</td>
</tr>
<tr>
<td>Resting tendon length EM, cm</td>
<td>9.7 ± 0.5</td>
<td>9.6 ± 0.5</td>
<td>8.1 ± 0.4</td>
</tr>
<tr>
<td>Strain YM, %</td>
<td>3.1 ± 0.9</td>
<td>4.6 ± 1.2</td>
<td>7.9 ± 1.7</td>
</tr>
<tr>
<td>Strain EM, %</td>
<td>4.7 ± 1.2†</td>
<td>7.6 ± 1.2†</td>
<td>11.8 ± 2.6†</td>
</tr>
<tr>
<td>PCD torque YM, N·m</td>
<td>52.6 ± 4.7</td>
<td>35.5 ± 3.0</td>
<td>14.9 ± 1.9</td>
</tr>
<tr>
<td>PCD torque EM, N·m</td>
<td>56.4 ± 2.0†</td>
<td>48.6 ± 1.7†</td>
<td>6.7 ± 0.9*</td>
</tr>
<tr>
<td>EMD YM, s</td>
<td>0.09 ± 0.005</td>
<td>0.045 ± 0.012</td>
<td>0.057 ± 0.019</td>
</tr>
<tr>
<td>EMD EM, s</td>
<td>0.047 ± 0.009*</td>
<td>0.082 ± 0.037*</td>
<td>0.119 ± 0.051†</td>
</tr>
</tbody>
</table>

Values are means ± SD. Plantar flexion (PF) maximal voluntary contraction torque (MVC), tendon elongation at 25 N·m PF torque (TE25 N·m), and electromechanical delay (EMD) were all significantly different between the young (YM) and elderly men (EM). The torque developed with a postcontraction doublet (PCD) relative to a maximal voluntary contraction (MVC) was significantly less between YM and EM, although in the EM PCD/MVC at +20°, it was significantly lower than at 0°. Significant differences from YM: *P < 0.05, †P < 0.01.

second doublet was delivered. After the second doublet, the subjects relaxed immediately.

A ratio of interpolated and PCDs was used to provide an index of activation; the interpolated doublet on the highest contractile force was used in the calculation of activation level (1, 12) as follows:

**ITT Activation (%)** = \[1 - \text{(superimposed doublet torque/post-MVC doublet torque)}\] × 100.

To determine activation without the influence of TE on the PCD, activation was also assessed as the ratio of superimposed doublet torque and voluntary torque (11).

**CAR activation (%)** = (superimposed torque/MVC torque) × 100

To determine the factors responsible for the change in ITT and CAR across the joint angles, the difference between voluntary torque and the interpolated doublet were calculated (relative PCD) and are presented alongside the absolute value of PCD torque.

**Electromechanical delay.** Two sets of two pregelled 10-mm Ag-AgCl percutaneous unipolar electrodes (Medicotest, Rugmarken, Denmark) were placed over the lateral and medial heads of the gastrocnemius muscle at 75% of the muscle length, along the mid-sagittal line. Before placement of the electrodes, the skin was shaved to remove hair, and the recording sites were lightly rubbed with abrasive gel and cleaned with alcohol swabs to reduce interelectrode impedance below 5 kΩ. The raw EMG activity was acquired with a sampling frequency of 2,000 Hz and processed with a multichannel analog-to-digital converter (Biopac Systems). The raw EMG signal was filtered with low- and high-band pass filters set at 500 and 10 Hz, respectively, and amplified with a gain of 2,000. Both torque and EMG signals were handled by the same integration system and displayed simultaneously in real time. Electromechanical delay (EMD) was determined as the time period from the onset of EMG activity and a perturbation of plantar flexion torque, by use of Acknowledge software (Biopac Systems). To determine whether difference in EMD existed in the triceps surae muscle, EMG was separately determined from simultaneous recordings of EMG activities of the soleus and gastrocnemius lateralis muscles (identified by ultrasound) in a group of nine EM.

**Statistics.** A two-way (group × ankle angle) ANOVA was used to compare interactions and means. Main effects were compared to determine within-group difference at each angle. A one-way ANOVA was used to determine the effects of age group. Linear regression (Pearson product-moment correlation) was used to compare the degree of association between variables. Data in the text, unless otherwise stated, are means ± SD. Data in the figures are presented as means ± SE.

**RESULTS**

**Plantar flexor strength.** The EM were significantly weaker than their young counterparts at all ankle joint angles (P < 0.01, Table 1). Two-way ANOVA showed that the angle interaction was not significantly different between the YM and EM. In both groups, plantar flexion MVC torque at −20° was significantly greater than at 0° (P < 0.01), and 20° was significantly less than at 0° (P < 0.01, Table 1). Intraclass correlation coefficients for strength measurements in the EM (n = 9) repeated over 2 consecutive days by the same investigator was high (0.97).

**Activation.** Activation assessed by ITT and CAR was significantly lower in the EM than in the YM (15° and 6°, respectively) at −20° (P < 0.05, Table 2). At 0° and in a plantar flexed position, there was no significant difference between activation in the YM and EM when either technique was used (Table 2). When the two methods of assessing activation were compared in EM, activation values obtained with ITT were 12% lower than those obtained by CAR at −20° (P < 0.05, Table 2). At all other angles, there was no significant difference in the activation values obtained by CAR and ITT.

PCD torque relative to plantar flexion MVC torque was no different between YM and EM, although the EM had a significantly lower value at 20° than at 0° (P < 0.05, Table 1). The difference between the superimposed and voluntary torque was significantly greater in EM than YM at −20° (P < 0.01, Fig. 2). In addition, in the EM, the difference between the superimposed torque and voluntary torque was higher at −20° than at 0° (P < 0.05, Fig. 2). There was no significant difference between voluntary and superimposed torque at any angle in the young.

**Activation reliability.** Activation measurements from −20°, repeated over 2 days in the EM (n = 9), revealed a high

Table 2. Activation assessed by 2 techniques

<table>
<thead>
<tr>
<th>Ankle Joint Angle</th>
<th>−20°</th>
<th>0°</th>
<th>+20°</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITT YM, %</td>
<td>96.8 ± 5.9</td>
<td>98.6 ± 3.0</td>
<td>100 ± 0</td>
</tr>
<tr>
<td>ITT EM, %</td>
<td>81.8 ± 12.0</td>
<td>93.1 ± 12.3</td>
<td>96.7 ± 7.2</td>
</tr>
<tr>
<td>CAR YM, %</td>
<td>98.8 ± 2.6</td>
<td>99.5 ± 1.2</td>
<td>100 ± 0</td>
</tr>
<tr>
<td>CAR EM, %</td>
<td>93.0 ± 5.1</td>
<td>97.2 ± 5.3</td>
<td>99.3 ± 1.5</td>
</tr>
</tbody>
</table>

Values are means ± SD. When assessed as a ratio of superimposed to PCD torque (ITT), EM had significantly lower activation than YM at −20° (P < 0.01). Similarly, when assessed as a ratio of superimposed to voluntary torque [central activation ratio (CAR)], activation was lower in the EM compared with the YM at −20° (P < 0.05). When the 2 techniques were compared, activation assessed by ITT was significantly lower than that assessed by CAR at −20° (P < 0.05). *Significant difference between YM and EM (P < 0.05); †significant difference between CAR and ITT within groups (P < 0.05).
shorter compared with a neutral joint angle (Table 1, when in a plantar-flexed position, Achilles tendon length was resting tendon length in either the young or elderly. Instead, angles (P < 0.05). Correspondingly, in both the young and the elderly (P < 0.05).)

angles (20°), compared with either 0° (P < 0.05), and 108% longer at 20° (P < 0.05). Unlike the YM, the EM had a significantly greater EMD at 20° than at 0° (P < 0.05, Table 1). There was a significant positive correlation between EMD and TE (R^2 = 0.489, P < 0.01). When compared in a subsection of young participants (n = 9), gastrocnemius muscle EMD was not significantly different from soleus muscle EMD (29.6 ± 9.4 and 29.8 ± 8.3 ms, respectively).

**DISCUSSION**

The present investigation is the first to show that increased TE, measured in vivo, in the plantar flexors of EM may directly influence twitch torque in vivo and demonstrates an interdependence between TE, PCD torque, and EMD on joint angle. 

**TE.** The present data are in line with previous observations made in situ (32) that TE (defined as proximal displacement of the gastrocnemius MTJ for the same absolute torque) is greater in elderly than in young individuals. This is also confirmed by greater measurements of strain at all three ankle joint angles tested. Furthermore, in both EM and YM, TE was significantly greater in a plantar-flexed position (20°), and this was consistent with an increased EMD, which has previously been shown to be associated with an increased slack of the muscle-tendon complex (22). In contrast, in a dorsiflexed position, much of the slack of the muscle-tendon complex would be taken up (as there was no change in resting tendon length between 0 and 20°) and a greater passive torque would place this complex beyond the more compliant toe region of the tendon force-elongation relationship (18). Hence, at −20°, TE is expected to be lower, which is confirmed by the present results. However, as suggested by the greater TE measurements, the EM have more compliant tendons and would therefore require a greater stretch to reach the same portion of the tendon force-elongation relationship occupied by their younger counterparts.

**TE and PCD.** The significance of increased tendon compliance on resting twitch torque has been previously reported by use of compliant and noncompliant external force transmission systems (15). Our data obtained in vivo confirm the significance of age-related changes in TE on interpolated doublet amplitude. In the present EM, we observed a reduction of the
PCD amplitude relative to MVC at ankle joint angles at which TE was greatest. The reduction of twitch torque in a compliant system has been attributed to a greater degree of shortening of the muscle-tendon complex reducing the effectiveness of force transmission (15). Previous studies have also attributed series compliance to observations of nonlinearity found in the expected compared with the observed torque of interpolated twitches at low-level submaximal contractions of the plantar flexors (27). In this study and others, the viscoelastic properties of the myotendinous complex and the slack within these structures was attributed to reducing the interpolated twitch amplitude (13, 27). It is therefore likely that greater TE both in the elderly and at shorter muscle lengths reflects damping of the PCD by the viscoelastic components of the tendon.

Activation. Although the present data show that TE is likely to result in lower PCD torques, it is apparent that this physiological artifact may not influence the assessment of activation when ITT is used because of a greater influence of joint angle on voluntary torque. For instance, when the foot is placed in a dorsiflexed position (−20°), where TE is at its lowest, there is only a 4% increase in the PCD relative to MVC, whereas the difference between the superimposed doublet and MVC torque was increased by threefold. When activation is expressed using ITT as 1 − (A/B) (where A is the difference between the superimposed and MVC torque and B is the PCD amplitude; Fig. 3), at −20° there is a much greater increase in A than B, hence activation is reduced. It is therefore evident that this larger reduction in voluntary torque, as opposed to increase in PCD torque, results in a lower activation at −20° when ITT is used. The suppression of the increase in the relative PCD, regardless of reduced TE at −20°, is representative of the previously reported influence of passive stretch on the reduction of interpolated twitch amplitude (7).

When the foot is placed in a plantar-flexed position (+20°), TE is greater, and this causes a reduction in the amplitude of the PCD relative to MVC in EM. If A remained constant, a decrease in B would result in an underestimate of activation in a plantar-flexed position. However, activation assessed by using ITT in the EM was no different than in the YM and certainly not significantly different from full activation. Therefore, the consequence on the assessment of activation resulting from the reduction in the amplitude of the relative PCD torque is minimal in the present elderly. This is due to the fact that when the foot is placed in these plantar flexion positions there is almost no difference between the interpolated and voluntary torque; that is to say, A is negligible, and the reduction in the relative PCD torque is of little consequence to the assessment of activation. Similarly, the YM demonstrated full doublet occlusion during MVC (i.e., A is negligible at all angles) and were therefore unaffected by any reduction in the PCD for the assessment of activation when in plantar flexion.

In the present investigation, EM demonstrated a significant activation deficit at −20° compared with at 0° or +20°. The suppression of voluntary torque at −20° is likely to be representative of a lower motor unit activation, because of greater inhibition by the Golgi tendon organ (26). Consistent with previous reports, we observed no significant change in tendon length from 0° to −20° (8); therefore it is the gastrocnemius muscle that is stretched. Previously, muscle stretch has been shown to reduce motoneuron excitability (7). It is likely that the limited extensibility of the Achilles tendon at this joint angle results in a reduction in motor neuron excitability, possibly the result of presynaptic inhibition as outlined by Guissard et al. (7). At +20°, this presynaptic inhibition is either not present or reduced, and, in contrast, greater TE is likely to result in lower proprioceptive precision in the elderly, particularly in plantar-flexed positions. The increase in TE, and hence in the EMD, reflects a greater time delay in force transmission, the consequences of which have been alluded to previously (23). Indeed, an increase in EMD has been proposed to reduce the magnitude and rate of a reflex response by increasing “lag” to muscle spindles (23), thus reducing the proprioceptive sensitivity of the elderly.

At −20°, we observed significantly lower values of activation with ITT compared with the CAR method. These findings confirm what has been shown previously, that ITT is a more accurate technique than CAR for the assessment of activation and yields results close to those obtained by tetanic stimulation (2). It is possible that the lower activation obtained with ITT compared with CAR at −20° was a result of complete expression of the PCD, resulting from low strain and TE, when the muscle is placed in stretch. In contrast, in testing at shortened muscle lengths, where TE and strain are greater and the relative PCD amplitude is reduced, ITT is likely to underestimate activation compared with the CAR. However, in the present investigation, the difference between the voluntary and the superimposed doublet was negligible, and hence full activation was observed with both techniques.

In conclusion, the present results have shown that an increase in TE of EM, expressed as a greater proximal displacement of the gastrocnemius MTJ, contributes to a decrease in the magnitude of a PCD, particularly at shortened muscle lengths. This decrease in the amplitude of the PCD would, if all else were equal, lead to an underestimation of activation when using ITT. However, the suppression of the PCD appears to have limited significance on the assessment of activation using the ITT, because changes in voluntary torque with changes in ankle joint angle counteract the changes in the PCD amplitude.

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GRANTS

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