linearly and similarly with increasing voluntary forces on two different days. The consequence of the data for the subject displayed in Fig. 2 is that for the measurement with a torque of ~150 Nm and extrapolating the linear relationship between voluntary and superimposed torque below 150 Nm, a voluntary activation level of ~96% is calculated, whereas in reality 150 Nm is only ~75% of the measured maximal torque, which would indicate a voluntary activation level of ~75%. Clearly, there is a mismatch between calculated voluntary activation levels and maximal torque capacity. Thus, even at the isometric force plateau, an almost full activation may be far from complete, at least in some subjects and in large muscle groups. In the scarce reports that show examples of data for individual subjects, linear relationships can be seen for the submaximal contractions, but there are additional data points having a low superimposed force at near maximal voluntary forces. The voluntary forces of these latter data points seem to be higher than the maximal force capacity calculated from the submaximal data (2, 19–21). Although only for subjects who are consistently very well able to activate their muscles, overestimation of voluntary activation can be demonstrated, it is conceivable that this in fact occurs for all subjects. Many subjects will not be able to further increase muscle excitation and despite measured levels of voluntary activation of ~95% most of them do not approach their real maximal force capacity. The ITT method clearly overestimates the true voluntary activation and therewith underestimates maximal force capacity in many subjects.

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17. Merton PA. Voluntary forces of these latter data points seem to be higher than the maximal force capacity calculated from the submaximal data (2, 19–21). Although only for subjects who are consistently very well able to activate their muscles, overestimation of voluntary activation can be demonstrated, it is conceivable that this in fact occurs for all subjects. Many subjects will not be able to further increase muscle excitation and despite measured levels of voluntary activation of ~95% most of them do not approach their real maximal force capacity. The ITT method clearly overestimates the true voluntary activation and therewith underestimates maximal force capacity in many subjects.

REBUTTAL FROM TAYLOR

Twitch interpolation measures the proportion of maximal possible muscle force produced during voluntary contraction. Drs. de Haan, Gerrits, and de Ruijer conclude this in their second paragraph, but two of their objections to the validity of twitch interpolation are based on the premise that voluntary activation represents something more central, perhaps motoneuron firing or even input to motoneurons. They first object that sensitivity at near maximal contraction intensities is low. The cited model (4) uses a sigmoidal input-output relationship for motoneurons, such that large changes in excitation to the motoneurons produce only small changes in force at high contraction strengths. Hence, twitch interpolation, like voluntary force, has low sensitivity to altered excitatory drive to the motoneuron pool at high forces. However, the model shows a linear relationship between voluntary force and the interpolated twitch and supports the validity of twitch interpolation. Experimental evidence given for low sensitivity is a relatively large EMG increase for the increase in force above 80% maximum in the knee extensors (5). The implication is that small increases in force require large increases in motor unit firing, but other factors like synchronization can also increase EMG (6). Furthermore, other muscles do not show similar EMG-force relationships (2).
Point:Counterpoint

The second objection that voluntary activation cannot be generalized from one situation to another seems a positive rather than a negative. Under different loading conditions different firing rates will be required for production of full force and one would not expect the same maximal voluntary activation.

On the third objection, I concede that nonlinearities in the relationship between the interpolated twitch and voluntary force are common in practice, and extrapolation to predict maximal force is not recommended. The paper cited (5) shows extreme nonlinearity for individuals’ knee extensors. Similar curves were seen for biceps brachii where methodological contributors were postulated (1). Such possibilities, including stimulation of antagonists, muscle lengthening, and variable synergist or antagonist contribution to voluntary torque, also hold for knee extension. Triplet stimulation may also contribute to nonlinearity as multiple pulses produce more torque than single pulses during weak but not strong contractions (3). Similarly, short interpulse intervals increase force greatly in unrecruited muscle, but not during repetitive firing (3).

Thus twitch interpolation using nerve stimulation cannot measure motoneuronal input or output but only how well the muscle is driven to produce force. Although never ideal in humans, it usefully discriminates altered drive to muscles.

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REBUTTAL FROM DE HAAN, GERRITS, AND DE RUITER

We agree with Dr. Taylor (9) that modeling (5) is supportive of the ITT technique in estimating voluntary activation with linear extrapolation of the relation between superimposed and voluntary torque up to maximal effort. It should however be kept in mind that this modeling study was performed for a small hand muscle, in which all motor units are recruited at ~50% MVC. It is unknown whether in bigger muscles with larger motor units, where recruitment of all motor units is thought to be complete only above ~90% of maximal torque (6), such linearity is also maintained at high forces. Moreover, there is a lack of knowledge regarding the firing rate-force relationships of the largest motor units (3, 4). The examples available for individuals (1, 7, 8, 10) show that in larger muscle groups the superimposed twitch voluntary torque relationships near maximal torques are clearly nonlinear. In our opinion, only data from individual subjects can be used to determine linearity of the relationship. Group data will only diffuse the relation, particularly near maximal force, where relatively large changes in voluntary activation lead to small changes in the superimposed twitch, which may give the impression of noise (2, 8) when not carefully measured and/or presented for individual subjects.

In her Point, Dr. Taylor suggests that the variability near maximal voluntary torque (h in Fig. 1) may be due to factors such as actions of other muscles (synergists and antagonists), which can alter voluntary force output without altering voluntary activation of the target muscle. However, this variability, which may be much larger than indicated in the figure, is seen in various muscle groups (1, 7, 8, 10) where only small contributions of the factors mentioned can be expected.

Moreover, Kooistra et al. (7; see also Fig. 2, inset, Counterpoint) clearly showed that up to maximal torque there is an increase in activation, which is very reproducible but can only be detected in subjects very well able to activate their muscles.

We can agree with the conclusion made in the Point that measurement of voluntary activation can help to reveal changes with physiological interventions and pathology. It certainly generates more information about maximal torque capacity in different circumstances than assessment of maximal voluntary torque without superimposed stimulation. However, because of the methodological limitations and variable overestimation of voluntary activation, in our opinion measured voluntary activation should be used qualitatively, or at best semi-quantitatively.

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