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The torque–velocity relationship in large human muscles: Maximum voluntary versus electrically stimulated behaviour

Matthew T.G. Pain [a,*], Fraser Young [a], Jinwoo Kim [a], Stephanie E. Forrester [b]

[a] School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough LE11 3TU, UK
[b] Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough LE11 3TU, UK

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ABSTRACT

The *in vivo* maximum voluntary torque–velocity profile for large muscle groups differs from the *in vitro* tetanic profile with lower than expected eccentric torques. Using sub-maximal transcutaneous electrical stimulation has given torque–velocity profiles with an eccentric torque plateau ~1.4 times the isometric value. This is closer to, but still less than, the *in vitro* tetanic profiles with plateaus between 1.5 and 1.9 times isometric. This study investigated the maximum voluntary and sub-maximum transcutaneous electrical stimulated torque–angle–angular velocity profiles for the knee extensors and flexors in a group of healthy males. Fifteen male subjects performed maximum voluntary and sub-maximum electrically stimulated (~40% for extensors and ~20% for flexors) eccentric and concentric knee extension and flexions on an isovelocity dynamometer at velocities ranging from $\pm 50^\circ\,s^{-1}$ to $\pm 400^\circ\,s^{-1}$. The ratio of peak eccentric to peak isometric torque (T_{ecc}/T_0) was compared between the maximum voluntary and electrically stimulated conditions for both extensors and flexors, and between muscle groups. Under maximum voluntary conditions the peak torque ratio, T_{ecc}/T_0, remained close to 1 (0.9–1.2) while for the electrically stimulated conditions it was significantly higher (1.4–1.7; $p<0.001$) and within the range of tetanic values reported from *in vitro* studies. In all but one case there was no significant difference in ratios between the extensors and flexors. The results showed that even the largest muscle groups have an intrinsic T_{ecc}/T_0 comparable with *in vitro* muscle tests, and it can be ascertained from appropriate *in vivo* testing.

1. Introduction

Maximum strength and power varies with the velocity of muscular contractions and the length of the muscle fibres. The tetanic force–velocity relationship in isolated muscle fibres follows a well established profile characterised by an eccentric force plateau at approximately 1.5–1.9 times the isometric value, and a hyperbolic decay in force with increasing shortening velocity (Hill, 1938; Katz, 1939; Déléze, 1961; Edman et al., 1978; Edman, 1988; Harry et al., 1990). Maximum torque expressed at the joint level is a complex integration of the muscle fibre contractile properties with the *in vivo* architecture of multiple muscle fibres, connective tissue and neural input. *In vivo* measurements of maximum voluntary contraction's (MVC) force–velocity show differences to the *in vitro* tetanic profile, with eccentric forces not increasing much above isometric and tending to decline with increasing lengthening velocity (Westing et al., 1988; Dudley et al., 1990; Weber and Kriellaars, 1997; Kellis and Baltzopoulos, 1998; Forrester and Pain, 2010). Consequently, maximum voluntary eccentric strength is much lower than one might expect based on maximum isometric measurements and *in vitro* tetanic force–velocity behaviour. EMG studies have pointed to a 10–30% reduction in the neural drive of the agonist muscle under the high loading conditions of eccentric and low concentric maximum voluntary knee extensions (Stauber, 1989; Westing et al., 1991; Kellis and Baltzopoulos, 1998; Babault et al., 2001). This is regarded to be an involuntary mechanism to protect the human body against excessive strain and injury (Westing et al., 1991).

Transcutaneous electrical stimulation to supplement maximum voluntary contractions has been found to increase eccentric knee extension torque to above the maximum voluntary levels, but to have no significant effect on concentric torque (Dudley et al., 1990; Westing et al., 1990). However, subjects are not able to tolerate the development of maximum torques through transcutaneous electrical stimulation as the sole source of knee extensor activation. Within this limitation constant stimulation levels that produced 40–60% of MVC were used by Dudley et al. (1990) to reproduce a torque–velocity profile for the knee extensors that was more similar to the *in vitro* tetanic profile;

* Corresponding author. Tel.: +44 1509 226327; fax: +44 1509 226301.
E-mail address: m.t.g.pain@lboro.ac.uk (M.T.G. Pain).

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maximum eccentric torque was 1.4 times the isometric value and did not drop off at higher lengthening velocities.

Despite the long standing proposal of a tension limiting mechanism it is still uncertain whether neural factors are solely responsible for the difference between MVC and *in vitro* tetanic eccentric forces as even stimulated *in vivo* eccentric to isometric ratios have invariably been lower than *in vitro* ratios. There may be other structural components of whole *in vivo* muscle tendon complexes, such as changes in pennation angle with force levels (Rutherford and Jones, 1992; Herbert and Gandevia, 1995; Aagaard et al., 2000) or myofacial force transmission (Rijkelijkhuizen et al., 2005), that contribute. Pain and Forrester (2009) investigated correcting the maximum voluntary torque–velocity profile by using normalised, wavelet transformed EMG. They found a theoretical ratio of peak eccentric to isometric torque of 1.6 indicating that the majority, but not all, of the decreased torque, compared to *in vitro* could be accounted for by sub-maximal activation of the knee extensors.

Determining to what extent the *in vitro–in vivo* difference is due to neural factors, and if it is consistent across muscle groups, could aid with implementing realistic eccentric muscle modelling and gaining insight for developing training and rehabilitation programmes. The aim of this study was to compare MVC and sub-maximum stimulation torque–angle–angular velocity profiles for the knee extensors and flexors, the first time that the knee flexors have been examined under transcutaneous electrically stimulated conditions, in a group of healthy males,. The eccentric–concentric velocity range over which the measures were taken exceeded that used in previous knee extensor studies and it is considered that this will aid in producing results commensurate with *in vitro* studies. It was hypothesised that the peak torque ratio (eccentric/isometric) would be higher for stimulation compared to MVC in both extensors and flexors, but that there would be no difference in the peak torque ratio between extensors and flexors as differences seen *in vivo* are likely predominantly due to a neural mechanism.

2. Methods

Fifteen male subjects who were either university level athletes or good recreational athletes (age 23 ± 2 years, body mass 77 ± 7 kg, height 178 ± 6 cm) were recruited. All subjects had been injury free in their lower limbs for at least 12 months prior to testing and provided voluntary informed consent in accordance with the approval given by the University Ethical Advisory Committee.

A set protocol was completed on an isovelocity dynamometer (Con-Trex, CMV AG, Switzerland) over three sessions each separated by one week: familiarisation; knee extensors; and knee flexors. In each session subjects were seated on the dynamometer with their dominant leg strapped tightly to the unpadded crank arm directly above the ankle joint using a protective moulded plastic shin guard. To minimise differences between the crank and joint kinematics, the rotational axis of the crank arm was aligned with the centre of the knee joint during near-maximal efforts separately for both knee extension and knee flexion trials. Hip angle was controlled at 85° hip flexion for the extensors and 70° hip flexion for the flexors allowing subjects to exert maximal effort over as wide a knee angle range as possible with minimum discomfort, especially during stimulation trials. An initial gravity correction trial was performed, which involved the relaxed leg being moved through the full range of motion.

The protocol for the main test sessions included MVC and sub-maximum stimulation (where the transcutaneous stimulation was the only source of activation) isometric, concentric and eccentric knee extensions/flexions. Following a warm up, maximum voluntary isometric torque was measured at five angles equally distributed across the subject's range of motion. Maximum voluntary eccentric–concentric trials were measured at 10 angular velocities (±100, 200, 300, 400, 50° s^{-1}) following the protocol developed by Yeadon et al. (2006) with two repetitions at each velocity and a rest interval of at least 2 min between each trial. Knee range of motion was from 5° to 100° of knee flexion for the quadriceps and 5° to 90° for the hamstrings (0° corresponded to an extended knee). This process was repeated for the stimulation trials. Finally, a single MVC isometric trial at an intermediate angle was repeated to test for fatigue effects.

Transcutaneous electrical stimulation of the quadriceps and hamstrings was achieved using a stimulator (DS7AH, Digitimer Ltd., UK) controlled by Spike 2 software (CED micro 1401, CED, Cambridge, UK) that produced square wave impulse trains of single pulse duration 100 μs at 50 Hz. Two carbon-rubber electrodes (140 mm × 100 mm; Electro-Medical Supplies, Greenham, UK) were coated with a thin layer of conductive gel and then taped over the rectus femoris, vastus medialis and vastus lateralis, or the biceps femoris and semi-tendinosus. To familiarise the subject with the sensation, stimulation began at a current of 40 mA and increased in steps of 10–30 mA until the prescribed level of torque was achieved. Stimulation level was calculated based on a percentage of maximal voluntary isometric torque at the middle of the five angles, ~40% for the extensors, and ~20% for the flexors. To limit fatigue and discomfort, each isometric trial involved stimulation for not more than 1 s, while in the eccentric–concentric isovelocity trials the first repetition was passive and the second stimulated. Torque and stimulation data were available in real-time to check the percentage stimulation based on voltage output and fatigue.

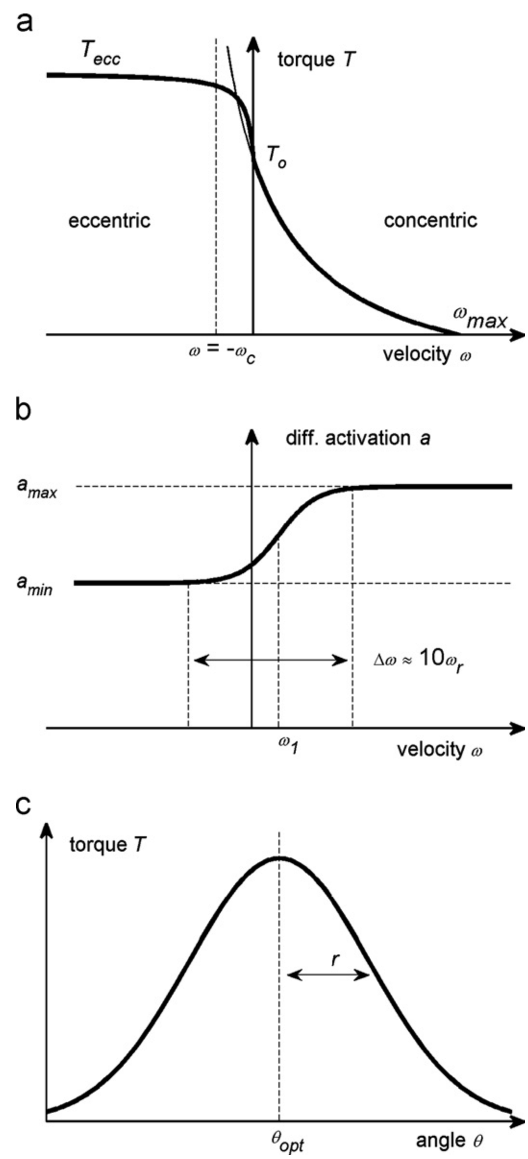

Fig. 1. Components of the nine-parameter function (Forrester et al., 2011). (a) Tetanic torque–angular velocity function, comprising a Hill-type hyperbola in the concentric phase and an inverted rectangular hyperbola in the eccentric phase. k is the ratio of slopes between the concentric and eccentric phases and is set to a value of 4.3 representing the theoretical value predicted by Huxley (1957) original model. The four parameters are: maximum eccentric torque (T_{ecc}); maximum isometric torque (T_o); maximum angular velocity (ω_{max}); and angular velocity defining the vertical asymptote of the concentric hyperbola ($\omega = -\omega_c$). (b) Differential activation–angular velocity sigmoid ramp up function. The three parameters are: the low plateau activation level (a_{MIN}); ω_r which gives the angular velocity range over which the ramp occurs (~$10\omega_r$); and the midpoint angular velocity of the ramp (ω_1). (c) Torque–angle function described by a normal distribution function. The two parameters are: width (standard deviation) of the curve (r); and optimal angle (mean) for torque production (θ_{opt}).