The force-velocity relation of multi-joint leg extension is neither linear nor hyperbolic

Daniel Hahn – Human Movement Science, Faculty of Sport Science, Ruhr-Universität Bochum, Germany

RUHR-UNIVERSITÄT BOCHUM RUB

1 Introduction

Force and power production of human muscles depends on the instantaneous contractile conditions determined by muscle length and the rate and direction of length change. While the force-velocity relation of isolated muscle preparations and single-joint concentric contractions is hyperbolic in shape (Hill 1938, Wilkie 1950), it has been reported to be linear for multi-joint leg extension (Bobbert 2012, Yamauchi et al. 2007). However, these studies are either based on simplified modeling approaches (Bobbert 2012) and/or considered a single, optimal joint angle configuration only (Yamauchi et al. 2007). Furthermore, force-velocity relations from multi-joint leg extension are limited to calculated or measured external reaction forces under the feet, which, however, results from a double transformation of muscle force into joint torque and from joint torque into external reaction force.

Although it is well known, that force-velocity-relations are more accurate when Hill's constants *a* and *b* are varied with muscle length (Chow et al. 1999, a, b, c), to our knowledge there are no data available on the combined effects of joint angle and angular velocity on voluntary force and torque production during multi-joint leg extension. Accordingly the purpose of this study was to determine angle specific force/torque-angular velocity properties.

2 Methods

Experimental settings and experimental protocol

- *n* = 18 male subjects (30 ± 6.3 years, 1.81 ± 0.08 m, 77.9 ± 5.2 kg).
- bilateral leg extensions on a motor driven leg press dynamometer (IsoMed2000, D&R Ferstl GmbH, Germany).
- seated position, vertical backrest reclined to 50°, footrest with force plates rotated by 15° from vertical towards plantar flexion and fixed; heel placement 0.1 m above the height of the seat.
- ROM of 100°-30° knee flexion (0° = straight leg).
- dynamometer kinematics calculated according to Hahn et al. (2005) to result in mean angular velocities of the knee of 30, 60, 120, 180, and 240° s^{-1}.
- four sessions on different days (2*familiarisation, 1*isometric testing, 1*dynamic testing).
- isometric tests in increments of 10° (ROM 100°-30°), 3 sets of 8 maximum voluntary contractions in randomised order.
- five sets of three maximum voluntary concentric contractions, each set a given angular velocity; random order and released only when subjects reached a 95% angle specific preload.
- one day rest between sessions, 3 and 5 min rest between contractions and sets, respectively.
- determination of maximum angular velocity (ω_{max}) during unresisted leg extensions that started without preload from the resting state at maximum knee flexion (*n* = 10).

Data processing

- force measurement by three-component force plates (KISTLER, Switzerland).
- motion analysis by VICON MX-3 Motion-System (Vicon Motion Systems, UK).
- calculation of knee joint torques (M_K) by methods of inverse dynamics, inertial properties according to Zatsiorsky et al. (1984) and de Leva (1996).

For more details please refer to Hahn et al. (2014).

3 Results – part one

- shift of optimum knee angle from 52±7°-64±4° knee flexion with increasing velocity.
- decreased external forces and knee joint torques with increasing angular velocity with a clear angle dependence of the shape of the force/torque-angular velocity-relations (Fig. 1).

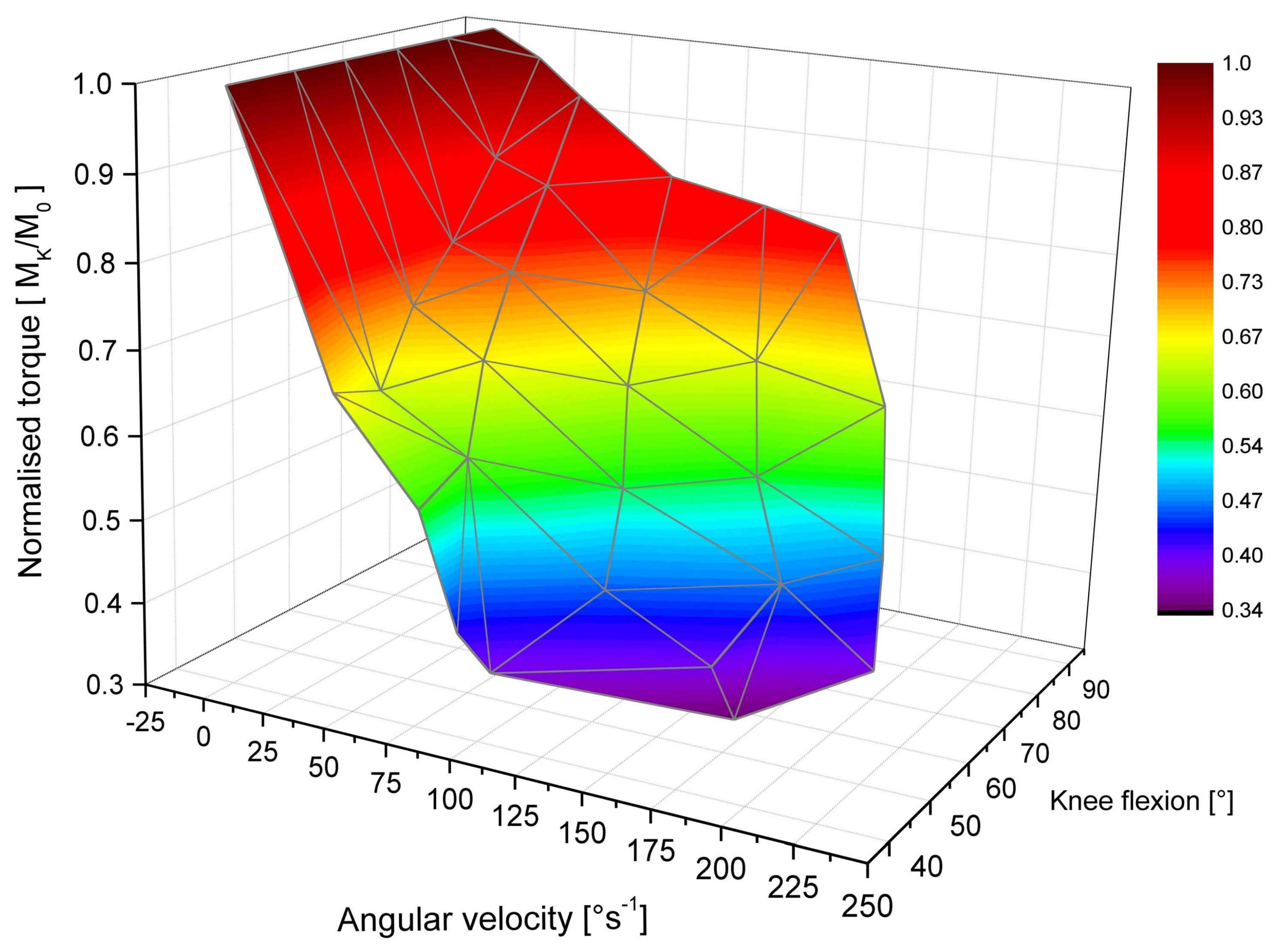

Fig. 1: Three-dimensional torque-angle-angular velocity-relation from group data to indicate the interdependence of normalised knee joint torque (y-axis), joint angle (z-axis), and angular velocity (x-axis). All data points have been normalised to their corresponding angle specific isometric maximum and the colour scale indicates normalised knee joint torque. Knee flexion of 0° refers to the straight leg.

- increase of maximum unresisted angular velocities from 866±79°s^{-1}-1238±132°s^{-1} for 90°-50° knee flexion.
- underestimation of maximum angle specific isometric force/torque (except for 90° of knee flexion) as determined by extrapolation of linear and hyperbolic functions.
- underestimation and overestimation of maximum unrestricted angular velocity when calculated by linear regression and hyperbolic functions, respectively (Tab. 1).

Tab. 1: Maximum external reaction force F_0 and velocity ω_{max} for unresisted shortening as extrapolated by linear and hyperbolic functions (*n* = 6). Data normalized; values are means ± SD.

	Knee joint flexion angle [°]				
	50	60	70	80	90
F_0 linear	0.84 ± 0.07	0.86 ± 0.07	0.89 ± 0.05	0.95 ± 0.07	0.99 ± 0.05
F_0 Hill	0.91 ± 0.06	0.92 ± 0.05	0.93 ± 0.04	0.97 ± 0.06	1.00 ± 0.05
ω_{max} linear	0.32 ± 0.04	0.38 ± 0.06	0.42 ± 0.06	0.59 ± 0.13	0.78 ± 0.16
ω_{max} Hill	1.25 ± 0.30	1.66 ± 0.45	2.05 ± 0.49	3.40 ± 1.16	5.09 ± 1.30

3 Results – part two

- good agreement of force-velocity relations calculated by linear regression and Hills hyperbolic function with experimental data (r = .86±.12 to .94±.03) with slightly better correlations for Hill's hyperbola (Fig. 2).

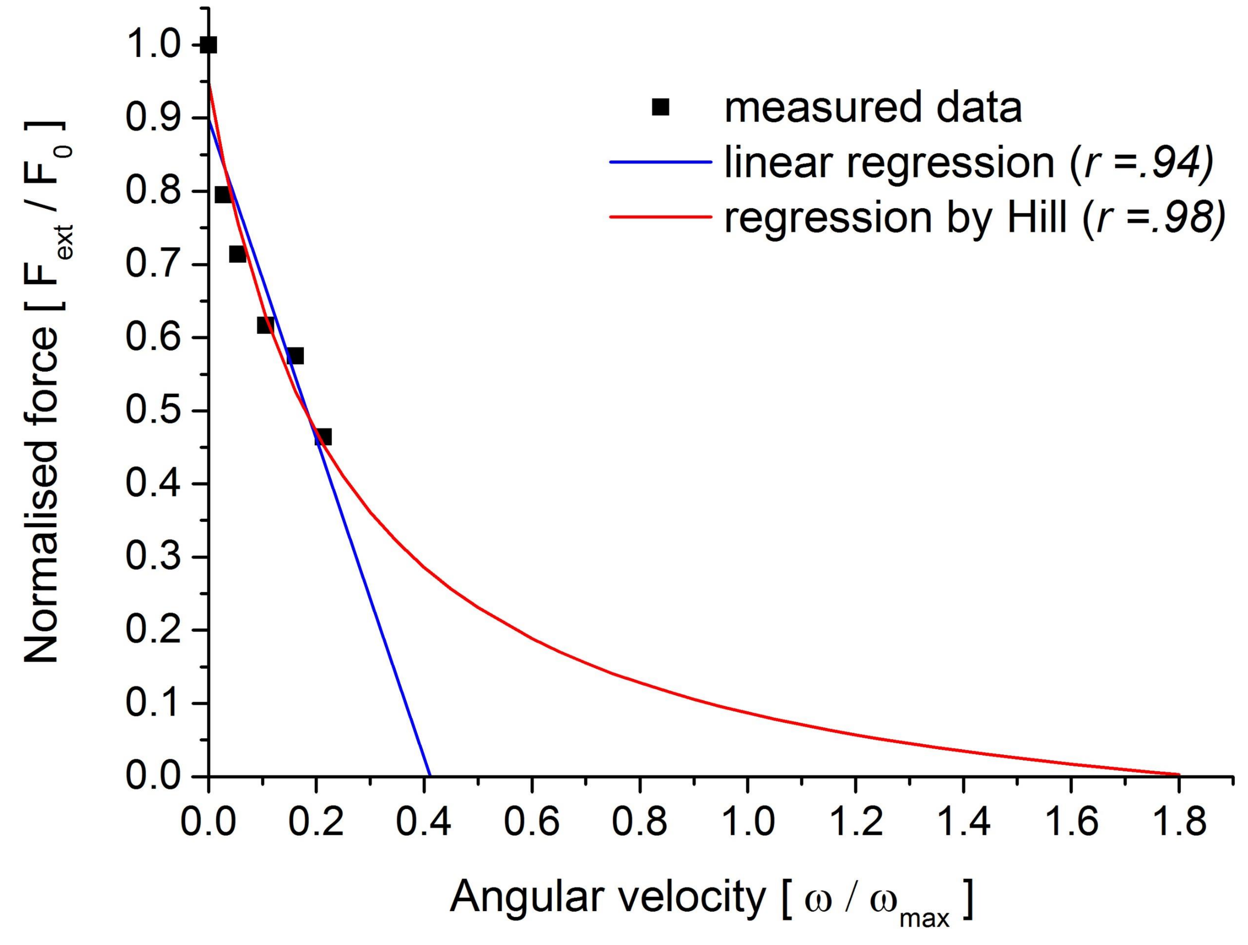

Fig. 2: Force-velocity-relation for a single subject normalised to maximum isometric force and maximum unresisted angular velocity. As indicated by correlations and also by a residual analysis, measured data (black squares) fit slightly better to Hills hyperbolic function (red line) than to linear regression (blue line).

4 Discussion

Our results demonstrate that the shapes of multi-joint leg extension force-velocity relations change with joint angle, suggesting that a proper representation of human muscle function should be based on measurements at different muscle lengths/joint angles. Despite good correlations between experimental data and linear as well as hyperbolic functions, none of the functions was able to predict maximum isometric forces/torques and angular velocities properly. We therefore suppose that force-velocity relations of multi-joint leg extension have neither a linear nor a hyperbolic but a concave-convex shape. From a biomechanical and physiological point of view, this might be due to MTC elasticity, biarticular effects, changes in lattice spacing and/or muscle length dependent Ca^{2+}-sensitivity.

Since data are still incomplete, future research should include experiments covering the entire range of leg extension velocities and should be aimed at elucidating the mechanisms underlying the findings presented here. Notwithstanding missing explanations, real-life movements and rehabilitation exercises typically involve multi-joint movements, thus our results should be taken into consideration when modelling human movement or designing training concepts.

References

Bobbert, M.F. (2012). *J Appl Physiol* **112(12)**, 1975–1983.
Chow et al. (1999a, b, c). *J Appl Biomech* **15(2)**, 182-209.
Hahn et al. (2005). *Isokinet Exerc Sci* **13(2)**, 95-101.
Hahn et al. (2014). *Eur J Appl Physiol*, DOI 10.1007/s00421-014-2899-5
Hill, A.V. (1938). *Proc. R. Soc. Lond. B* 1938 **126**, 136-195.
Wilkie, D.R. (1950). *J Physiol* **110**, 249-280.
Yamauchi et al. (2007). *J Biomech* **40(7)**, 1433-1442.

Contact Information: daniel.hahn@rub.de