

Technical note

Is the force-length relationship a useful indicator of contractile element damage following eccentric exercise?

Timothy A. Butterfield, Walter Herzog*

Human Performance Laboratory, Faculty of Kinesiology, University of Calgary, 2500 University Drive NW, Calgary, Alta. Canada T2N 1N4

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Abstract

Eccentric exercise has been shown to have a measurable effect on the force-length relationship (FLR), as peak force is shifted to longer muscle lengths following exercise. Recently, this shift in the FLR has been proposed as a “simple, reliable indicator” for assessing contractile element damage following eccentric exercise. However, eccentric exercise causes fatigue and damage, and there is evidence that fatigue alone may also cause a shift in the FLR. The purpose of this paper was to assess the role of fatigue on the FLR (as measured by a torque–joint angle relationship) following isometric and eccentric exercise in the New Zealand white (NZW) rabbit. Six NZW rabbits were divided into two groups for eccentric or isometric contractions of the hindlimb dorsiflexor muscles. Pre- and post-exercise torque–joint angle relationships were measured, and the shift from the pre- to the post-exercise relationship was measured as the change in joint angle at which peak torque was produced. Eccentric exercise resulted in a rightward shift of seven degrees; isometric exercise, which is thought to not cause damage, resulted in a shift of four degrees. Furthermore, torque production was reduced to a greater extent at short compared to long muscle lengths for the eccentric and isometric exercise, resulting in a post-exercise torque–joint angle relationship that was altered in shape. We conclude from these results, that the shift in peak torque may not be a simple and reliable indicator of muscle damage, but is caused by a combination of damage and post-exercise fatigue.

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1. Introduction

Eccentric exercise has been shown to have a measurable effect on the force-length relationship (FLR), as peak force is produced at a longer muscle length following exercise (Talbot and Morgan, 1996; Jones et al., 1997; Wood et al., 1993). Several mechanisms producing this rightward shift in the FLR following exercise have been proposed. These include stretch-induced damage to calcium handling structures, (Balnave and Allen, 1995; Warren et al., 1993; Endo, 1972), visco-elastic creep (Fowles et al., 2000), and contractile element damage

(Brockett et al., 2001; Morgan and Allen, 1999; Morgan et al., 1996; Brockett et al., 2002). Recently, the rightward shift in the FLR has been proposed as a “simple, reliable indicator” for assessing contractile element damage following eccentric exercise (Whitehead et al., 2003).

The rightward shift in the FLR was first identified with contractile element injury by Katz (1939), who proposed that contractile elements were transformed into passive elastic elements by muscle stretch. Morgan (1990) proposed that this transformation of contractile elements during eccentric contractions occurs through a ‘popping’ of a small number of sarcomeres as they are stretched beyond myofilament overlap, resulting in an increase in muscle compliance. As a consequence, the muscle would produce peak force at a longer length, thereby exhibiting a rightward shift of the FLR.

*Corresponding author. Tel: +1-403-220-8525; fax: +1-403-284-3553.

E-mail address: walter@kin.ucalgary.ca (W. Herzog).

This rightward shift of the FLR following eccentric contractions has been observed in a variety of studies and muscle preparations, including human plantarflexors (Whitehead et al., 1998; Jones et al., 1997), and hamstrings (Brockett et al., 2001), single toad fibers (Jones et al., 1997), single frog fibers (Morgan et al., 1996), and individual motor units from the cat medial gastrocnemius (Brockett et al., 2002). In each of these studies, the shift was associated with contractile element damage. In addition, histological findings post-exercise supported the concept of contractile element injury within the muscle following eccentric exercise (Jones et al., 1997), although the possible contribution of fatigue on the FLR was not considered.

Unlike eccentric contractions, isometric exercise does not produce extensive contractile element damage (Koh and Brooks, 2001), and presents a unique model to study the effects of fatigue on the FLR in the absence of muscle injury. Although previous studies have assessed the effects of fatigue on the force–length relationship, the use of single fibers (Yeung et al., 2002a, b) or lack of direct comparison to the post eccentric exercise FLR (Cutlip et al., 2004) leaves the contribution of fatigue to the rightward shift of the FLR following eccentric exercise unclear. Therefore, the purpose of this study was to directly test the hypothesis that fatigue contributes to the rightward shift in the FLR of the ankle dorsiflexors in New Zealand white rabbits following eccentric exercise.

2. Materials and methods

2.1. Experimental design

Eight skeletally mature NZW rabbits (5.6 ± 0.2 kg, Riemens, St. Agatha, Ontario, Canada) were divided into two study groups for measurement of a pre-exercise and post-exercise torque–joint angle relationship. Group one consisted of five rabbits (nine hindlimbs) subjected to eccentric exercise. Group two consisted of three rabbits (six hindlimbs) subjected to an equivalent isometric exercise. All procedures were approved by the Animal Care Committee of the University of Calgary.

2.2. Surgical procedure

Rabbits were tranquilized with 0.18 ml (10 mg/ml) acepro-25 (MTC Pharmaceuticals, Cambridge, ON, Canada) and held under anesthesia with 1.5% isoflurane, 0.6 L/min N_2O and 0.8 L/min O_2 . An incision was made on the posterior aspect of the right and left hindlimbs, anterior to the sciatic vein, and the biceps femoris and semimembranosus were separated exposing the peroneal nerve. Nerve cuff stimulating electrodes were secured over the right and left common peroneal

nerves, superior to the gastrocnemius and distal to the branching of the sciatic nerve. In this manner, all dorsiflexors of the tibiotarsal joints were stimulated effectively. Following implantation, the skin was stapled closed.

2.3. Exercise and measurement protocol

2.3.1. Eccentric exercise, group 1

Rabbits were placed supine in a stereotaxic frame with the knee at 90° flexion (full extension = 0°). The foot was strapped to a servo-motor footplate (Parker Hannifin Corporation, Irwin, PA, USA) and ankle movement was controlled via computer (Motion Planner, Rohnert Park, CA, USA). The tibiotarsal joint angle was set at 90° (full extension = 180°) which served as the reference angle for the remainder of the experiment. The peroneal nerve cuff leads were attached to a stimulator (Grass S8800, Astro-Med Inc., Longueuil, QC, Canada), and the α -motoneuron threshold was determined (pulse duration = 0.1 ms, frequency = 150 Hz).

First, a pre-exercise, isometric torque–joint angle relationship was determined by supramaximally stimulating ($3 \times \alpha$ -motoneuron threshold voltage, pulse duration = 0.1 ms, frequency = 150 Hz, train duration = 2000 ms) the dorsiflexor muscles, beginning at a tibiotarsal angle of 55° and progressing in 5° increments to 155° . To limit the potential effects of creep of passive elements at long muscle lengths, the foot was parked at a 55° joint angle (short muscle length) between isometric contractions. Therefore, following each isometric contraction, the foot was returned passively to a dorsiflexed position (55° tibiotarsal angle) for 2 min of rest between contractions.

The exercise protocol consisted of eccentric contractions performed from a tibiotarsal angle of 70 – 105° of plantar flexion at $70^\circ s^{-1}$ ($3 \times \alpha$ -motoneuron threshold voltage, pulse duration = 0.1 ms, frequency = 150 Hz, train duration = 500 ms). Each stretch-shortening cycle lasted 1000 ms. Stimulation started at the onset of plantar flexion and ceased at the end of the eccentric exercise (105°), resulting in an eccentric exercise of 500 ms duration. Immediately following the eccentric contraction, the foot was passively returned to the 70° starting position at $70^\circ s^{-1}$ (500 ms passive shortening). To induce muscle injury associated with eccentric contractions, it has been shown that greater than one contraction is required when working within the physiologic range of motion (Cutlip et al., 2004; Gosselin and Burton, 2002). Therefore, the exercise protocol consisted of five sets of ten eccentric contractions, with 2 min rest between sets. Immediately after the eccentric protocol, a post-exercise torque–joint angle relationship was measured in a manner identical to the pre-exercise relationship. However, the rest between

isometric contractions was reduced to 30 s to limit the recovery from fatigue during measurement of the FLR post-exercise. Therefore, the foot was returned to a dorsiflexed position (55° tibiotarsal joint angle) between contractions, but for only 30 s of rest before moving to the next joint angle.

2.3.2. Isometric exercise, group 2

Using identical stimulation parameters as described above, the pre-exercise torque–joint angle relationship was measured. Then, isometric contractions (3x α -motoneuron threshold voltage, pulse duration = 0.1 ms, frequency = 150 Hz, train duration = 500 ms, 500 ms rest) were performed at a tibiotarsal angle of 95° . This joint angle was chosen for the isometric contractions for several reasons: Firstly, pilot data indicated that it was, on average, the angle at which peak isometric torque was produced by the dorsiflexors; secondly, it lies within the range of motion for our eccentric protocol; and lastly, we found that little or no passive tension was associated with this muscle length, thus limiting the effects of creep during testing. The 500 ms train duration, and 500 ms rest between contractions in each protocol, assured that stimulation duration and timing were identical between the two exercise groups. The protocol consisted of five sets of 10 isometric contractions with 2 min rest between sets. A post-exercise torque–joint angle relationship was measured immediately following exercise as described above.

2.4. Torque–joint angle evaluation

Two precision strain gauges (Vishay Micro-Measurements, Raleigh, NC, USA. Item No. CEA-06-125WT-350) were arranged in a full bridge configuration, creating an instrumented cam connecting the footplate to the motor. Strain gauge calibration confirmed the linearity of output voltage as a function of strain ($R^2 > 0.99$) through a range greater than required for our protocol. The output signal was routed through a strain gauge amplifier/conditioner (Vishay 2100, Vishay Micro-Measurements, Raleigh, NC, USA. Gain 8.44×100 ; Excitation 10 Vdc; low pass filter 10 Hz) and sampled at 250 Hz with WinDaq data acquisition software (Dataq Instruments, Akron, Ohio, USA).

Peak torque values were plotted for all 21 tibiotarsal joint angles. Mean torques across all joints were plotted pre- and post-exercise. In order to calculate the angle of peak torque occurrence, torque values $> 75\%$ of the absolute peak torque were normalized, fit with a second-order polynomial, and peak torque was calculated as the peak value of the polynomial approximation. In addition, the mean rightward shift, calculated as the average of the shifts for each subject, was calculated for comparison (Jones et al., 1997; Whitehead et al., 2001). For force decrement data, post-exercise torques were

expressed as a percent decrease from the pre-exercise values. All statistical analyses were performed using SPSS version 11.5 (SPSS Incorporated, Chicago, IL, USA). For all parameters measured, means \pm SE are reported. Statistical significance was set at $p < 0.05$, and analyzed using Student's paired, or independent, t -tests.

3. Results

Following eccentric exercise, peak torque values at all angles were significantly lower compared to those obtained pre-exercise for all joint angles measured ($p < 0.001$, Fig. 1). Analysis of the torque–angle relationships revealed a rightward shift for all subjects in the eccentric group, and all but one subject in the isometric group (Table 1). Overall, mean peak torque production, as calculated from the polynomial fitted to the mean torque values following eccentric exercise, occurred at a joint angle of 104° compared to the pre-exercise peak of 98° , resulting in a 6° rightward shift. The rightward shift calculated as the average of individual fitted polynomials was 7° (Table 1). In addition, the shape of the torque–angle relationship was rotated in a counterclockwise manner following eccentric exercise (Fig. 1, inset).

Following isometric exercise, peak torque values at all angles were significantly lower compared to those obtained pre-exercise for all joint angles measured ($p < 0.001$, Fig. 2). Analysis of joint torque decrement between protocols revealed the greatest decrement in joint torque production following isometric exercise was $40.5 \pm 3.0\%$ at a tibiotarsal joint angle of 60° . The greatest torque decrement following eccentric exercise was $55.0 \pm 3.0\%$, and was measured at the smallest tibiotarsal joint angle, 55° (Fig. 3). Torque decrement following eccentric exercise was not significantly different compared to the decrement following isometric exercise, except at short muscle lengths ($p < 0.002$), corresponding to the smallest joint angles ($55\text{--}70^\circ$, Fig. 3). The mean peak torque value, calculated from the polynomial fitted to the mean torque values following isometric exercise, was shifted to the right by four degrees, from 101° to 105° , and the curve was rotated in a counterclockwise direction (Fig. 2, inset). Calculating the rightward shift as the average of individual shifts resulted in a mean rightward shift of 3° , (Table 1).

4. Discussion

Although a rightward shift in the FLR has been associated with histological evidence of contractile element damage following eccentric exercise, the results of this study suggest that a portion of the rightward shift

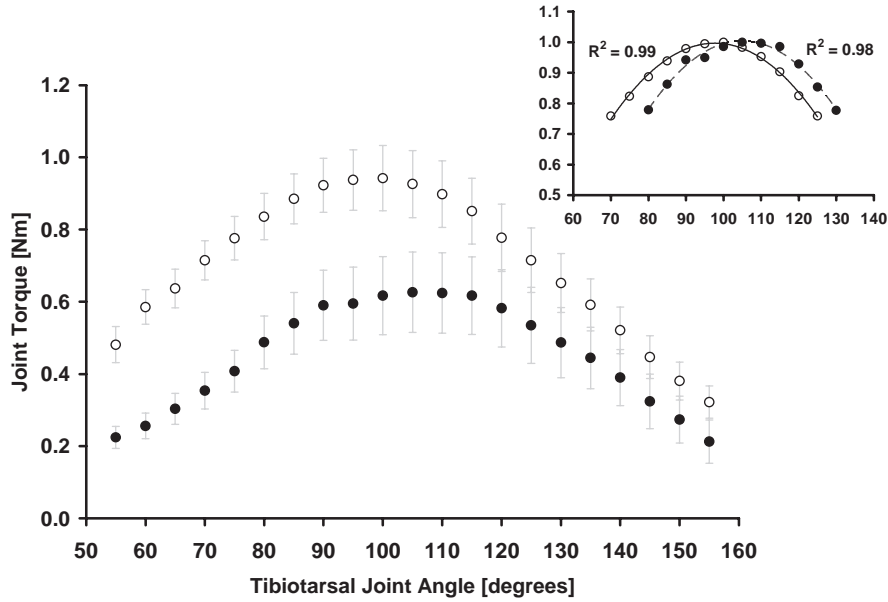


Fig. 1. Torque–angle relationship for NZW dorsiflexors before (○) and after (●) a bout of eccentric exercise. Note the apparent shift to the right in peak force production (from 100 to 105°) and the change in shape of the torque–joint angle relationship following exercise. Torque production following eccentric exercise was significantly reduced compared to pre-exercise values at all joint angles tested ($p < 0.001$). Values are mean \pm SE ($n = 9$). Inset. Normalized torque–angle relationship. Here the rightward shift and counterclockwise rotation are evident. Data were fitted with a second-order polynomial to calculate the angle of peak torque production pre-exercise (98°) and post-exercise (104°).

Table 1

Shift in peak torques from pre- to the post-exercise torque–angle relationship for individual subjects in the eccentric and isometric test groups.

Eccentric exercise	Shift in Peak Torque	Isometric Exercise	Shift in Peak Torque
ECC1L	+ 7°	ISO1L	+ 3°
ECC2L	+ 4°	ISO1R	+ 3°
ECC2R	+ 7°	ISO2L	0°
ECC3L	+ 12°	ISO2R	+ 5°
ECC3R	+ 4°	ISO3L	+ 3°
ECC4L	+ 9°	ISO3R	+ 3°
ECC4R	+ 12°		
ECC5L	+ 4°		
ECC5R	+ 5°		
MEAN	+ 7°	MEAN	+ 3°

A positive value indicates a rightward shift of the peak torque towards increased muscle lengths. The mean rightward shift was calculated as the average of the individual shift values. ECC=eccentric, 1,2,3,4,5=subject number; L, R=left and right. ISO=isometric, 1,2,3=subject number; L,R,=left and right.

and change in shape of the torque–angle relationship after exercise is contributed by the effects of fatigue. In our study, the isometric exercise resulted in a rightward shift of 4° fitting mean torque values with one polynomial (Fig. 2). This amounts to 67% of the 6° rightward shift obtained following the eccentric exercise protocol using the same procedure (Fig. 1). The overall contribution of fatigue to the rightward shift is reduced

to 43% by calculating the shift as the mean shift obtained from the individual subjects (Table 1).

Jones et al. (1997) also observed a rightward shift in the FLR using passive stretch combined with isometric exercise in human plantar flexor muscles that amounted to 50% of the shift following an eccentric exercise protocol. However, the authors deemed the isometric shift insignificant. In the same paper, a significant rightward shift in optimum force production of 3.5% muscle length was also reported for single toad fibers following a protocol of passive stretch and isometric contractions (Jones et al., 1997). Although these results are similar to ours, a direct comparison is difficult as the use of passive stretch may have produced damage (Koh and Brooks, 2001), that could have contributed to the shift.

Other studies have reported conflicting results compared to those presented here. Whitehead et al. (2003) showed a small shift in peak force production following isometric exercise in the cat medial gastrocnemius, which would only account for a small proportion of the shift reported following eccentric exercise (<10%). However, their fatigue protocols resulted in much smaller force decrements at optimal length following exercise (7% and 13%) compared to ours (29%). Conversely, single fiber experiments have shown no shift in peak force production following isometric exercise (Yeung et al., 2002a). However, a direct comparison between their in vitro protocol and our study is difficult.

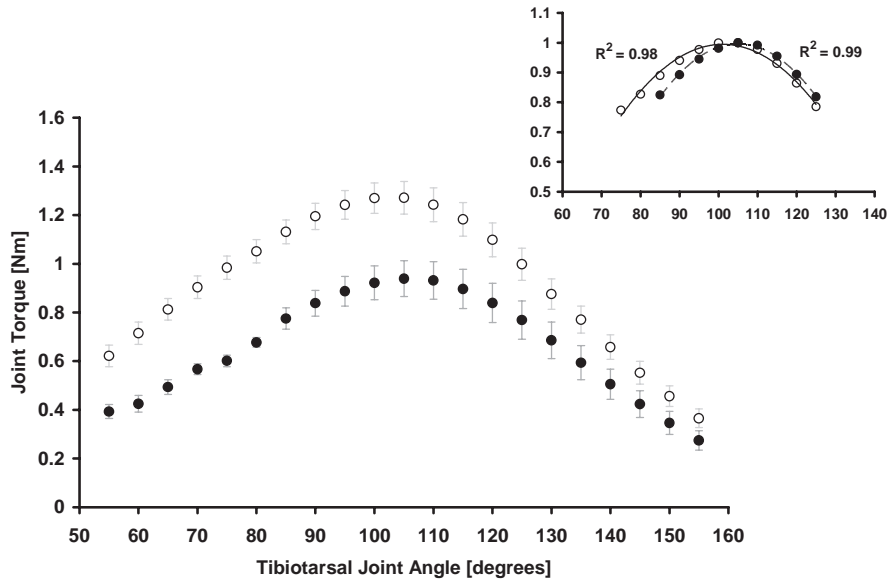


Fig. 2. Torque–angle relationship for NZW dorsiflexors before (○) and after (●) a bout of isometric exercise. Note the apparent lack of rightward shift in peak force production (105°). Torque production following isometric exercise was significantly reduced compared to pre-exercise values at all joint angles tested ($p < 0.001$). Values shown are mean \pm SE ($n = 6$). Inset. Normalized torque–angle relationship. Here the rightward shift and counter-clockwise rotation are evident. Data were fitted with a second order polynomial to calculate the angle of peak torque production pre-exercise (101°) and post-exercise (105°).

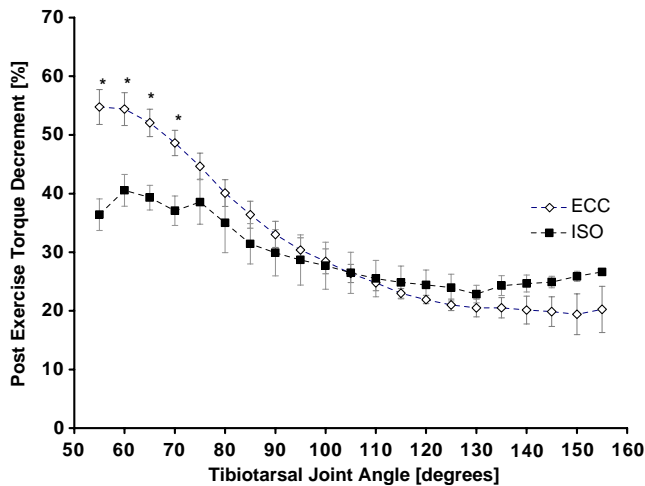


Fig. 3. Percent decrease in joint torque production immediately following 50 eccentric contractions (◇) and 50 isometric contractions (■). Visual inspection of the graph shows similar shaped traces for both the eccentric (ECC) and the isometric (ISO) groups, as the greatest loss of torque production following both protocols occurred at short muscle lengths. Analysis of the data indicate a significantly greater reduction in joint torque in the ECC group compared to the ISO group at joint angles of 55–70°, as indicated by (*). Significance of $p < 0.05$ was reported. Values are means \pm SE (ECC $n = 4$; ISO $n = 6$).

The contribution of fatigue to the rightward shift of the FLR may be associated with the change in shape of the FLR following both types of exercise, as the shapes of the torque–angle curves were similar between the exercise groups (Figs. 1 and 2). Simply, the torque–angle relationship appears to be rotated counterclockwise

following both eccentric exercise (Fig. 1, inset) and isometric exercise (Fig. 2, inset). Decreased isometric force production has been shown to be greatest at short muscle lengths following isometric (Gauthier et al., 1993; Cutlip et al., 2004) and eccentric exercise (Cutlip et al., 2004), implicating metabolic changes as the common factor in the altered shape of the ascending limb of the FLR following exercise. Here, we showed that isometric exercise produced the greatest reduction in joint torque at short muscle lengths. Similarly, the greatest reduction in joint torque following eccentric exercise ($55.0 \pm 3.0\%$), also occurred at the smallest joint angle tested (55°, Fig. 3), corresponding to the shortest muscle length.

In this study, the eccentric exercise was performed on the ascending limb and plateau region of the FLR. It has been shown that markers of muscle injury, including the shift in FLR, are greater on the descending, compared to ascending, limb of the FLR (Whitehead et al., 2003; Cutlip et al., 2004; Talbot and Morgan, 1998). Therefore, it is possible that the contribution of fatigue to the FLR shift following eccentric exercise at long muscle lengths would be diminished, due to a greater rightward shift following eccentric exercise.

Since fatigue has been shown to have a greater effect at short compared to long muscle lengths (Gauthier et al., 1993; Cutlip et al., 2004), torque production is reduced to a greater extent at short compared to long lengths, producing a post-exercise torque–angle relationship that is altered in shape. Torque decrement at short muscle lengths following eccentric exercise is

similar to that seen following isometric exercise (Fig. 3), but increased in magnitude for the eccentric compared to the isometric protocol. Thus, we concluded that metabolic changes are implicated in the altered shape of the ascending limb of the FLR following eccentric exercise. This, in conjunction with the use of curve fitting to predict the peak of the FLR, although well accepted (Wood et al., 1993; Jones et al., 1997; Talbot and Morgan, 1998; Whitehead et al., 1998), may produce the rightward shift due to fatigue.

5. Conclusion

We demonstrated that a rightward shift in the FLR following exercise may be partially attributed to the effects of fatigue. Although it is well accepted that contractile element damage plays an important role in the altered mechanical properties of muscle following eccentric contractions, the role of fatigue with respect to the shift in peak force production seems to have been overlooked. Based on the current results, fatigue may be responsible for up to 50% of the measured rightward shift in peak torque production following eccentric exercise. Therefore, the shift in peak torque is not necessarily a simple and reliable indicator of muscle damage.

References

- Balnave, C.D., Allen, D.G., 1995. Intracellular calcium and force in single mouse muscle fibres following repeated contractions with stretch. *Journal of Physiology* 488 (Part 1), 25–36.
- Brockett, C.L., Morgan, D.L., Gregory, J.E., Proske, U., 2002. Damage to different motor units from active lengthening of the medial gastrocnemius muscle of the cat. *Journal of Applied Physiology* 92, 1104–1110.
- Brockett, C.L., Morgan, D.L., Proske, U., 2001. Human hamstring muscles adapt to eccentric exercise by changing optimum length. *Medicine and Science in Sports and Exercise* 33, 783–790.
- Cutlip, R.G., Geronilla, K.B., Baker, B.A., Kashon, M.L., Miller, G.R., Schopper, A.W., 2004. Impact of muscle length during stretch-shortening contractions on real-time and temporal muscle performance measures in rats in vivo. *Journal of Applied Physiology* 96, 507–516.
- Endo, M., 1972. Stretch-induced increase in activation of skinned muscle fibres by calcium. *Nature-New Biology* 237, 211–213.
- Fowles, J.R., Sale, D.G., MacDougall, J.D., 2000. Reduced strength after passive stretch of the human plantarflexors. *Journal of Applied Physiology* 89, 1179–1188.
- Gauthier, A.P., Faltus, R.E., Macklem, P.T., Bellemare, F., 1993. Effects of fatigue on the length-tetanic force relationship of the rat diaphragm. *Journal of Applied Physiology* 74, 326–332.
- Gosselin, L.E., Burton, H., 2002. Impact of initial muscle length on force deficit following lengthening contractions in mammalian skeletal muscle. *Muscle Nerve* 25, 822–827.
- Jones, C., Allen, T., Talbot, J., Morgan, D.L., Proske, U., 1997. Changes in the mechanical properties of human and amphibian muscle after eccentric exercise. *European Journal of Applied Physiology and Occupational Physiology* 76, 21–31.
- Katz, B., 1939. The relation between force and speed in muscular contraction. *Journal of Physiology* 96, 45–64.
- Koh, T.J., Brooks, S.V., 2001. Lengthening contractions are not required to induce protection from contraction-induced muscle injury. *American Journal of Physiology-Regulatory Integrative and Comparative Physiology* 281, R155–R161.
- Morgan, D.L., 1990. New insights into the behavior of muscle during active lengthening. *Biophysical Journal* 57, 209–221.
- Morgan, D.L., Allen, D.G., 1999. Early events in stretch-induced muscle damage. *J.Appl.Physiol* 87, 2007–2015.
- Morgan, D.L., Claffin, D.R., Julian, F.J., 1996. The effects of repeated active stretches on tension generation and myoplasmic calcium in frog single muscle fibres. *Journal of Physiology* 497 (Part 3), 665–674.
- Talbot, J.A., Morgan, D.L., 1996. Quantitative analysis of sarcomere non-uniformities in active muscle following a stretch. *Journal of Muscle Research and Cell Motility* 17, 261–268.
- Talbot, J.A., Morgan, D.L., 1998. The effects of stretch parameters on eccentric exercise-induced damage to toad skeletal muscle. *Journal of Muscle Research and Cell Motility* 19, 237–245.
- Warren, G.L., Lowe, D.A., Hayes, D.A., Karwoski, C.J., Prior, B.M., Armstrong, R.B., 1993. Excitation failure in eccentric contraction-induced injury of mouse soleus muscle. *Journal of Physiology* 468, 487–499.
- Whitehead, N.P., Allen, T.J., Morgan, D.L., Proske, U., 1998. Damage to human muscle from eccentric exercise after training with concentric exercise. *Journal of Physiology* 512 (Part 2), 615–620.
- Whitehead, N.P., Morgan, D.L., Gregory, J.E., Proske, U., 2003. Rises in whole muscle passive tension of mammalian muscle after eccentric contractions at different lengths. *Journal of Applied Physiology* 95, 1224–1234.
- Whitehead, N.P., Weerakkody, N.S., Gregory, J.E., Morgan, D.L., Proske, U., 2001. Changes in passive tension of muscle in humans and animals after eccentric exercise. *Journal of Physiology* 533, 593–604.
- Wood, S.A., Morgan, D.L., Proske, U., 1993. Effects of repeated eccentric contractions on structure and mechanical properties of toad sartorius muscle. *American Journal of Physiology* 265, C792–C800.
- Yeung, E.W., Balnave, C.D., Ballard, H.J., Bourreau, J.P., Allen, D.G., 2002a. Development of T-tubular vacuoles in eccentrically damaged mouse muscle fibres. *Journal of Physiology* 540, 581–592.
- Yeung, E.W., Bourreau, J.P., Allen, D.G., Ballard, H.J., 2002b. Effect of eccentric contraction-induced injury on force and intracellular pH in rat skeletal muscles. *Journal of Applied Physiology* 92, 93–99.