NEUROMUSCULAR BIOMECHANICS IN SPORTS

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The purpose of this review was to highlight some of the more controversial aspects of neuromuscular biomechanics of sport. Neuromuscular techniques and interpretations of findings have been presented with the intent of showing the promise that research in this area has as well as the present limitations. In each case. I have tried to advocate an opinion by showing results from my own laboratory as well as to cite alternate opinions from top level laboratories elsewhere.

KEY WORDS: EMG, electrical stimulation, neural strength gains

INTRODUCTION: If we consider muscles to be mechanical actuators (i.e. motors) and the central nervous system to be the controller of the motors, then effective sport movements would require motors with adequate mechanical capacities and a controller capable of issuing the appropriate commands. Since both components are necessary, athletes attempt to maximise both and neuromuscular biomechanists do not often separate them. In this review, however, I will try to concentrate as much as possible on the neural aspects of sports biomechanics.

The easiest way to separate the neural from the muscular aspects of biomechanics is to consider the synapse to be the border such that post-synaptic events are dominated by muscle mechanics and pre-synaptic events determine muscular activation. The mechanical capacity of the motor can be assessed with dynamometers and the sports biomechanics literature contains numerous examples. The appropriateness of the neural commands is most often assessed from electromyography (EMG) which is the measurement of muscular electrical activity.

INFORMATION CONTENT OF EMG: The electromyogram is a random, nonstationary signal that has frustrated many kinesiologists over the years. Some believe that the signal is so fraught with problems of day-to-day repeatability, intra-muscle and intra-subject normalisation, crosstalk and noise that it can only be used descriptively with regard to when a muscle is active and when it is not. Given the importance of the central nervous system commands to athletic movement, it is nonetheless a valuable window to the neural aspects of movement and many scientists have devoted much of their efforts toward the improvement of the state of affairs and the International Society of Electromyographical Kinesiology has established data collection standards (Winter, et al. 1987). Presently, there are manufacturers making special EMG equipment to solve some of the collection problems and several papers have been written that offer guidelines for high quality EMG data collection. DeLuca (1997) provided an excellent list of recommendations and considerations to help biomechanists quantify EMG in the following three applications:

1. Phasic "on-off' activities of muscle.
2. Assessment of muscular fatigue.
3. Isometric muscle force quantification.

The only major disagreement that this author has with DeLuca (1997) is with the statement 'If a quantitative relationship between the EMG signal and force is required, then the contraction must be isometric' (pp. 150). Dowling (1997) reviewed a method that allowed estimations of individual muscle forces from EMG in non-isometric actions. The EMG signal must be combined with kinematics and elements of muscle mechanics in a Hill-type model (Figure 1) and the results show promise that this method will allow the non-invasive estimation of individual muscle forces (Figure 2). This is especially important to sports biomechanics because the movements are rarely isometric. The current linked segment approach of inverse dynamics allows the calculation of net joint torques but not actual joint forces (bone-on-bone forces) and it is incapable of separating passive **contributions** from active muscle toques (Dowling, **1988)**, assessing the level of contraction (Dowling, **1987)**, recovery of stored elastic energy (ingen Schenau, **1998)**, or calculating muscular efficiency (Cavanagh and Kram, 1985). Currently, when an athlete wishes to know why **her/his** performance is not at the desired level, biomechanists can use inverse dynamics to indicate which joint torque was likely deficient but they cannot say which muscle or even **if** the problem is due to the limited capacity of the motor or an inappropriate activation. The method of Dowling (1997) is not without limitations but these should be surmountable in the near future.

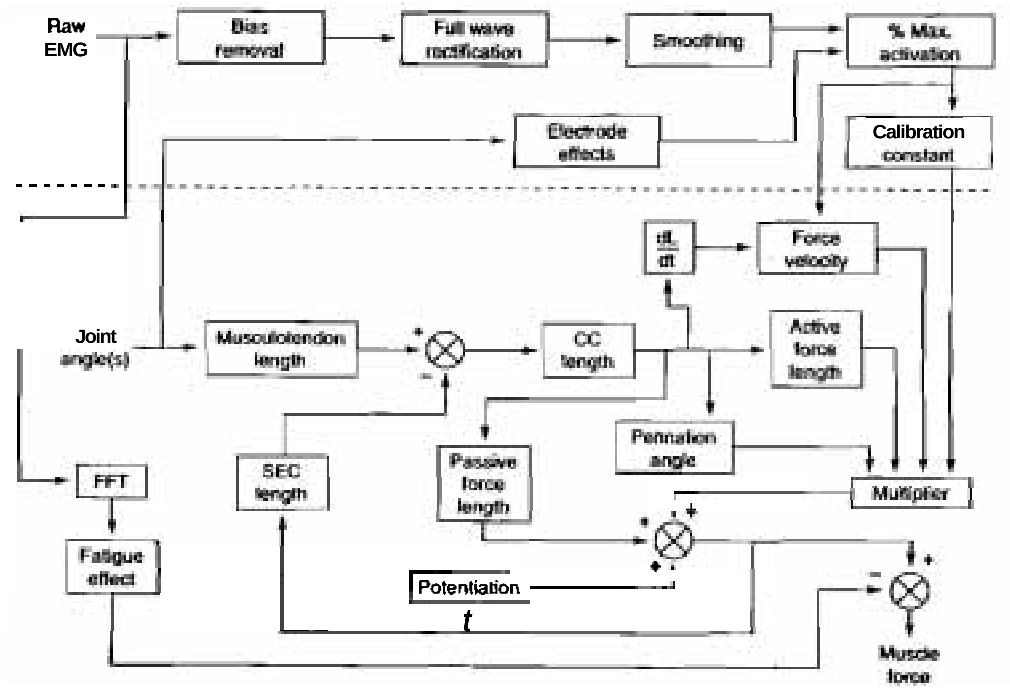

Figure 1 - Schematic diagram of a Hill-type model to predict individual muscle force from **EMG** and joint kinematics. From Dowling (1997).

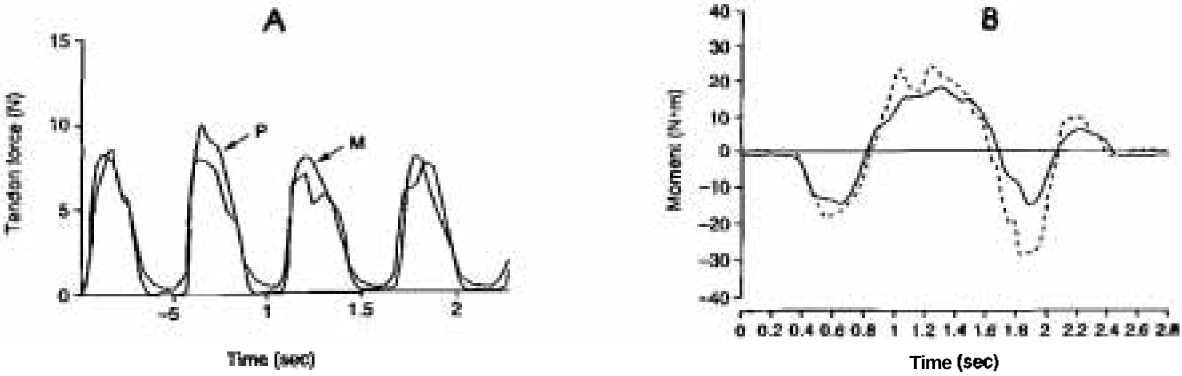

Figure 2 - A) Cat **soleus** muscles forces measured by a buckle transducer (M) and estimated by an **EMG** model (P) from Norman, **et** al. (1988). B) Human elbow toque against an inertial load measured from **accelerometry** (broken line) and predicted from the sum of individual muscle toques via an **EMG** model (solid line) from Dowling (1987).

MAXIMUM MUSCULAR ACTIVATION: There is not a single organ in the human body that functions at or even near its capacity during everyday activities. Is it, therefore, safe to assume that muscle has a reserve capacity that is not neurologically attainable under voluntary conditions?

The strongest evidence in favour of the opinion that one can maximally activate skeletal muscle comes from a technique known as the interpolated twitch (IT). Briefly, this technique involves the application of an electrical stimulus to the muscle or nerve during a voluntary contraction. The stimulus is a voltage that produces the maximum twitch of a resting muscle and is considered to have recruited all available motor units. As the level of voluntary effort increases, the amount of extra force generated by the stimulus diminishes (Figure 3A). Assuming this decrease to be linear (Figure 3B), several investigators have calculated the percent motor unit activation using equation [1]. Allen et al. (1985) claim that based on this formula, almost everyone can achieve full activation at least one time in 10 attempts of maximum voluntary contractions (MVC) and even those who cannot, achieve near full activations (95 % -98%).

$$\%Activation = \left[1 - \frac{IT}{IT_o}\right] \cdot 100 \qquad [1]$$

where: IT = extra force evoked by the interpolated twitch

IT_o = IT at 0% MVC

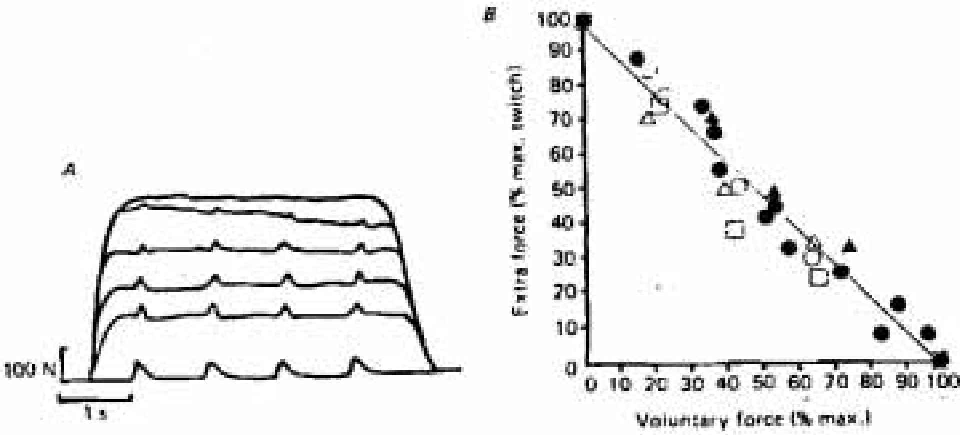

Figure 3 - A) Four interpolated twitches on top of 6 levels of voluntary effort. B) Decline of extra force as a function of increasing voluntary effort from Chapman, et al. (1984).

The structural evidence against the notion that maximum forces are exerted under voluntary conditions shows that tendons fail at forces that are three times that of MVC (Zajac, 1989). Tendons would only need this capacity if muscles under extreme conditions could exert forces much greater than those achieved under voluntary conditions. Experimental evidence shows that as muscle is stimulated at increasing frequencies, the force produced tends to level off (force- frequency curve: Sale. 1992) but increases in force are still observed at firing rates far above those seen under voluntary conditions (Herzog, 1996). DeLuca et al. (1982) has used a method to decompose indwelling EMG into individual motor unit trains and found the large motor units to fire at rates much below tetanic levels. These authors commented that if these large motor units could be made to fire consistently at high rates. 'extraordinary force levels could be achieved for short periods of time. This mechanism may indeed be the explanation for the many incredible feats performed by humans under high stress conditions and during hypnotic states' (pp. 126).

Even the IT has yielded experimental evidence that humans do not maximally activate muscles under voluntary conditions. Dowling et al. (1994) showed that fidelity of the IT technique needs to be increased because the signal-to-noise ratio decreased dramatically as the level of voluntary effort increased. The size of the signal was increased by using a doublet stimulation, the noise was reduced by averaging many trials and the results showed that the decrease was quite nonlinear (Figure 4) and that a small amount of extra muscle torque was evident for all subjects. This indicated that there was a reserve capacity in each muscle that was not recruited by the voluntary efforts of the subjects. It also showed that one cannot assume a linear decline in the extra force and the size of the reserve would be the level of force where the function reached zero. Since the function was exponential in nature, the intercept could be well beyond the MVC level.

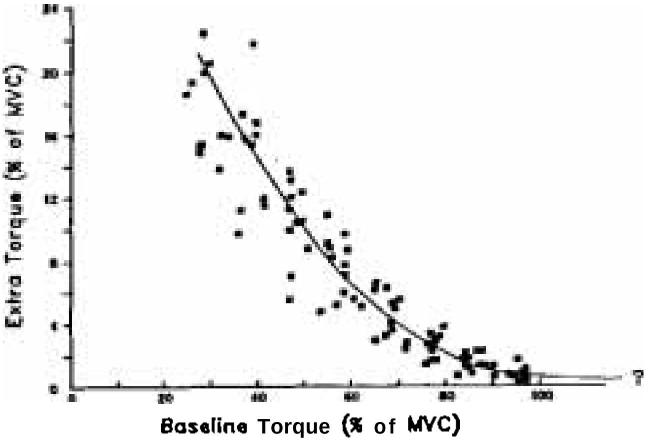

Figure 4 - Nonlinear decline in extra torque when averaged doublet stimulation is used. The solid represents the best fitting function to the data of 12 subjects showing that the level torque large enough to prevent any extra torque from IT could be well beyond 100% MVC. From Dowling et al. (1994).

Electrical stimulation offers the advantage of bypassing inhibitions to excitation within the nervous system by increasing the voltage but it does not have the advantage of activating each motor with independent firing rates. There are many nonlinearities in the way twitches summate and potentiate such that present methods of electrical stimulation may not be able to yield the upper limit of force generation. This author believes that the IT technique only provides evidence of a lack of activation but it cannot be used to confirm full activation. This is especially true with well motivated subjects such as athletes in which extra force may exist but the IT is not sensitive enough to see it or effective enough to produce it.

NEURAL vs PHYSIOLOGICAL STRENGTH GAINS: One piece of evidence against full activation that was not mentioned in the previous section is the observation of strength gains during the first few weeks of a weight training program without evidence of hypertrophy or other post-synaptic changes that could account for such increases. These early strength gains are quite dramatic for novice strength trainers and are often called neural strength gains (Sale, 1992). These increases in strength are often thought to be due to the central nervous system 'learning' to recruit more motor units or to achieve higher firing rates or more effective firing patterns. Regardless of the cause, this evidence argues against the notion that everyone is at least nearly capable of full activation.

Moritani (1993) reported a method to separate neural strength gains from hypertrophy using EMG (Figure 5).

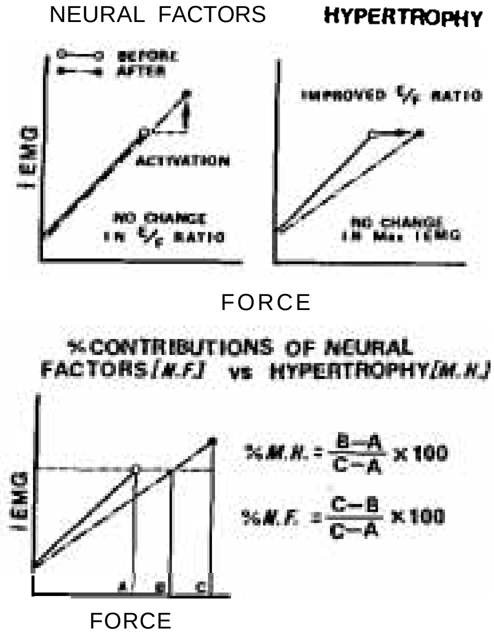

Figure 5 - Method of separating isometric strength gain into percentages due to neural and physiological causes from Moritani (1993).

This method assumes a linear EMG-to-force relationship and any increase in force that was accompanied by a proportional increase in EMG would be a 100% neural strength gain. If the force increased by a greater proportion than the EMG increase, then that greater portion would be due to hypertrophy. Since there are some day-to-day repeatability problems with the measurement of EMG, this method only works for populations of people. None-the-less, if these repeatability problems can be solved and if the method could be extended to muscles with nonlinear EMG-to-force relations, it could be used to monitor both neural and physiologic strength gains throughout an athlete's training program.

BALLISTIC PERFORMANCE INCREASES: Increases in performance of ballistic activities such as jumping and throwing are notoriously difficult to achieve in comparison to more aerobic activities. Some coaches have been heard to say that sprinters are 'bom' but marathon runenrs are 'made'. The type of motor units that make up human muscle are quite mixed and determined so early in development that there is nothing that an individual can do about what he/she has inherited. Fatigue resistant, slow-Witch fibres are best for aerobic activities and fast-Witch fibres are best for ballistic movements. Even though the distribution of these types is pre- determined and not equal for everyone, there is a certain amount of plasticity in the contractile characteristics such that motor units can be made to take on the characteristics of motor units that are different than those that were inherited. Without going into much detail of the motor unit plasticity research, the findings have shown that these transformations are not complete and revert rather quickly back to their unaltered states (Eken and Gundersen, 1988). Even if it is difficult to change motor unit characteristics to benefit ballistic movements, is it possible that the neural strength gains could allow for performance improvements?

Ballistic performance is based on maximising impulse and most biomechanics text books only identify increasing force (strength) and increasing time (via range of motion increases) as the methods of increasing impulse. Elite performers tend to exert forces over a shorter period of time than do novice performers. This means that in order for the impulse to be larger, the forces must increase by more than the time decreases or the shape of the force profile must be such that the area is greater in spite of the decreased time. Utilisation of stored elastic energy is often credited with the former effect and the rate of rise of force is often credited with the latter. If the pattern of force application is at least partly responsible for increased impulse over a shorter time period, then training the central nervous system may allow increases in ballistic performance without changing the contractile properties of the motor units.

Dowling (1992) showed that when movement is constrained by a fixed range of motion, force patterns that achieve maximum force early in the range are associated with short movement times and those that achieve maximum force late in the motion are characterized by a high final velocity and greater impulse (Figure 6).

This would argue against the importance of the rate of rise of force on ballistic performance as claimed by Schmidtbleicher (1992). It was also found that this late maximum force pattern required a considerably larger maximum instantaneous power than the early maximum force pattern. Instantaneous power is the product of force and velocity and these findings suggested that a high peak power was required to achieve a large impulse and a good performance in ballistic movement. This was at odds with Adamson and Whitney (1971) who had stated: "There is the almost intuitive objection that the instantaneous velocity of movement of the centre of mass is not due to the current force but to the preceding force time integral".

In an investigation of 97 subjects performing vertical jumps (Dowling and Vamos, 1993), it was found that very little variance in jump height could be explained by peak force, duration of force application or the rate of rise of force. Almost all of the variance could be explained by peak instantaneous power which was in agreement with the earlier mathematical model and showed that the ability to generate large forces under conditions of high velocity were necessary for good performances in a ballistic movement. Wilson and Murphy (1995) also showed that the rate of force development was not related to ballistic performance.

Since jumping is a multi-segment movement, it remained to be determined if the capacity for instantaneous power was due to the capacity of the motors or due to appropriate coordination and activation by the controller. In a training study of a single-segment movement, Bauer (1996) showed that becoming stronger does not necessarily mean that you become more powerful or better at ballistic performances. In that study, an ll% increase in peak velocity required a 30 % increase in peak power and more moderate increases of 13 % in peak force and 15 % increase in the rate of force development. If there was a neural or learning component to the improvement process, then there should be certain types of training methods that achieve better results than others which has, indeed, been shown (Kaneko, 1983; Wilson, et al. 1993). Again, until we can measure individual motor units during dynamic, ballistic actions, we will not know if the central nervous system can learn to exploit motor unit properties such as alternative recruitment and firing rate strategies and if this is what happens during certain training methods.

ECCENTRIC-CONCENTRIC MUSCLE ACTIONS: Most ballistic movements performed by athletes are not purely concentric in nature but involve an active lengthening of some muscles just prior to their shortening. Without getting into the utilisation of stored elastic energy debate (see Ingen Schenau,et al. 1997), 1 will briefly discuss the neural aspects.

There is evidence that the central nervous system organises eccentric actions differently than concentric and that there is an increased inhibition to maximum activation during eccentric actions than concentric actions (Westing, et al. 1988). Earlier, it was mentioned that there was some disagreement on regarding maximal activation of isometric muscle action and while the evidence may be greater for eccentric actions, we are not able to say how much of the decrease is due to an inhibition that could be reduced by training.

Alexander (1996) used a mathematical model of the high jump to show that the height of the jump is increased with an increase in the approach velocity up to about 8 m/s. While this is in accord with the approach velocity of elite performers and almost everyone is capable of achieving a running velocity of 8 mls, novice jumpers are not very capable of generating much vertical impulse at this velocity. The reasons are probably due to a combination of neural factors not allowing enough eccentric force generation and to elasticity issues. Once again, until we can separate the neural component from the motor component and find out how to generate improvements to the neural component, coaches and athletes are left with trial and error methods in the hope of finding a recipe for success. It is hoped that with improved EMG methods and electrical stimulation protocols, some of this guessing can be removed.

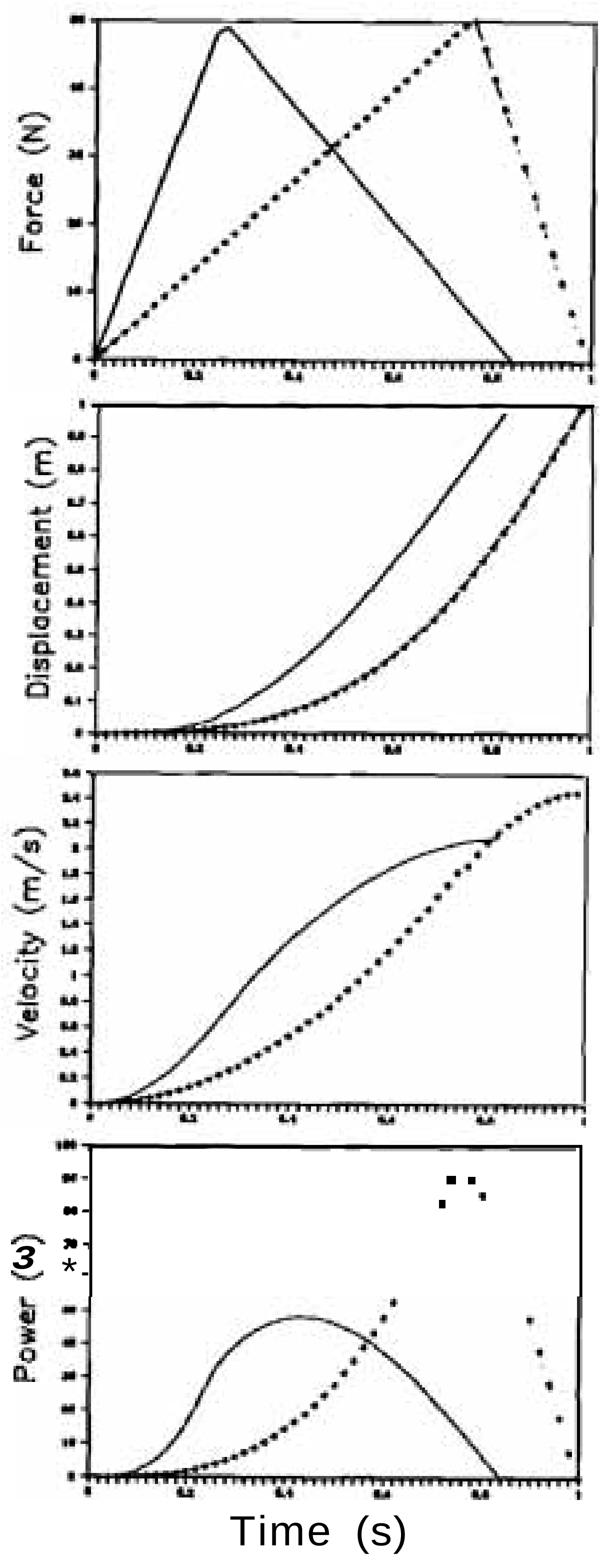

Figure 6 - Kinematics and kinetics of a **10** kg object resulting from two force patterns. Both motions were constrained to a range of **0.7** meters. The force pattern achieving the maximum early in the motion achieved the shortest movement time while the pattern that achieved maximum force late in the motion had the highest final velocity and required a much higher peak instantaneous power (Dowling, **1992).**

CONCLUSIONS: There is an intimate link between neural and mechanical aspects to human movement and practitioners must be able to exploit both in order achieve the best improvements in performance. EMG is a window to the neural aspects of movement and can help assess the effectiveness of training programs at tapping this source for performance enhancement. It is hoped that in the near future, techniques will exist that allow the monitoring of neural improvements as well as mechanical aspects are monitored today.

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