

Symposium introduction: Electromyography interpretation and limitations in functional analyses of musculoskeletal systems

Nicolai Konow^{1,*} and Shannon P. Gerry[†]

^{*}Department of Biology, 114 Hofstra University, Hempstead, NY 11549, USA; [†]Department of Biological Sciences, University of Rhode Island, 100 Flagg Road, Kingston, RI 02881, USA

Introduction

Electromyography (EMG) has played an important role in studies of musculoskeletal function for over half a century (Moyers 1949; reviewed by Loeb and Gans 1986). The technique has provided important insight into how neuromotor systems control the intrinsic and extrinsic dynamics of musculoskeletal mechanics. The conservation and evolution of motor control during feeding has been examined extensively within the context of a symposium, in order to synthesize studies across phylogenetic groups (Alfaro and Herrel 2001 and papers in that issue). Currently, EMG is an important technique in an integrative framework of experimental research; however, the interpretational potential, and the limitations to the technique in an integrative context have rarely been debated (this issue; *Amer Zool*, Vol. 41). As shown by most papers in the present issue, the use of EMG in conjunction with several more modern quantitative techniques is a powerful method for quantification of the complex dynamic relationships that exist at the different organizational levels of musculoskeletal form and function.

Inconsistencies among EMG protocols that spanned decades may lie at the root of the pronounced variation in collection and analyses of muscle activity data (Wainwright et al. 1989; Wainwright 2002). Consequently, it remains uncertain whether the variation in the magnitude of muscle-specific recruitment reported for closely related taxa are caused by technical incompatibilities between studies in different laboratories (Sanford and Lauder 1989; Wainwright et al. 1989; Konow and Sanford 2008) or by real biological differences. This variation, whether a technical artifact or biologically true, may potentially obscure some biologically informative variation. Analyses and interpretation of emerging phenomena such as regional

specialization within individual muscles (Herrel et al., 2008; German et al., 2008) and asynchronous activity in bilateral muscles during feeding (Gerry et al., manuscript in preparation) or locomotion (Higham et al. 2008) further contributes to the complexity of EMG collection, analyses, and interpretation.

Expanding from a previous SICB symposium on motor function (2001, see *Amer Zool*, Vol. 41), it is still clear that a debate on the interpretation of EMG data in an integrative experimental context is overdue. Such debate may foster a broader understanding of the interplay between biological mechanisms and inconsistencies in EMG protocol in producing a pattern of labile muscle-activity within individuals and species, and conservative motor patterns at evolutionary levels. Ultimately, the adoption of an EMG consensus-protocol would allow quantitative comparisons of homologous muscles performing mechanically comparable tasks across a broad phylogenetic sample.

Therefore, in the inaugural Late Breaking Symposium at the 2008 meeting of the Society for Integrative and Comparative Biology we examined the general interpretational advantages and limitations of EMGs and the relative importance of incompatibility between EMG protocols, with the overall goal of setting a consensus for future studies. The aim was to facilitate successful incorporation of EMG analyses into quantitative analyses of assemblage-level functional disparity, synchronized with other classical techniques such as cinefluoroscopy and high-speed video, and modern techniques like sonomicrometry, and recordings of strain, force and pressure. Furthermore, we hoped to discuss the progress on some of the target areas of research identified at the 2001 SICB motor-symposium and generate recommendations for future areas of study.

From the symposium "Late-Breaking Symposium Electromyography: Interpretation and Limitations in Functional Analyses of Musculoskeletal Systems" presented at the Annual Meeting of the Society for Integrative and Comparative Biology, January 2–6, 2008, in San Antonio, Texas.

¹E-mail: nicolai.konow@hofstra.edu

Integrative and Comparative Biology, pp. 1–5
doi:10.1093/icb/icn016

Variability in EMGs

Given the highly complex and variable nature of EMG, both single-species analyses and comparative studies over a broad taxonomic sample require hierarchical statistical approaches (Wainwright et al. 1989; German et al., 2008; Konow et al., manuscript in preparation). This is to differentiate levels of variation attributable to implant (electrode, day), behavioral type (in musculo-skeletal systems where individual muscles, or muscle segments, perform different tasks during functionally divergent behaviors, e.g., walking and running; capture and processing of prey), behavioral stimuli (e.g., substratum incline, or type of prey) or effects caused by individual variation. Historically, such statistically rigorous approaches were scarce (Doty and Bosma 1956; Shaffer and Lauder 1985; Wainwright et al. 1989), whereas, more recently, there has been increasing attention paid to this need (Alfaro et al. 2001; Thexton et al. 2007; Konow and Sanford 2008; German et al., 2008; Konow et al., manuscript in preparation).

The type of EMG variable, differentiated into either timing or recruitment variables, dictates markedly different criteria for the computation of variables. Temporal variables appear less subject to individual variability (Wainwright et al. 1989; Wainwright 2002; Ross et al. 2007) and, possibly less so than recruitment variables, to implant-specific effects (Thexton et al. 2007; Herrel et al., 2008). When comparisons are sought between taxa that utilize widely ranging durations of muscle activity (e.g., for masseter activity during a chewing cycle), the use of corrections for size (Wainwright and Richard 1995; Ross et al. 2007) and duty factors (Jayne and Lauder 1994; Alfaro et al. 2001) may help to mitigate effects of this type of variation.

Timing variables are most commonly used in comparative analyses, perhaps because of the relative regularity and ease of computation, while recruitment variables often are avoided altogether, given the assumption that differences in protocol hinder direct comparisons (Wainwright et al. 1989; Westneat and Hall 1992; Alfaro et al. 2001; Grubich 2001). Therefore, the most urgent requirement for facilitating future analytical progress is a convention about how recruitment variables should be treated. The reasons are manifold because recruitment magnitude and intensity likely vary with: (1) *Day of Implant*, either a new implant per experiment or a shift in electrode position within or between fascia from one experiment to the next (Wainwright et al. 1989; Jayne and Lauder 1994); (2) *Implant position*, into different fiber types, and associated different motor-unit activity patterns from

which the electrode records; (3) *Electrode morphology*, including inter-polar electrode width; (4) *Resistance and impedance*, in electrode wires and recording equipment (Motta et al. 1997) and between electrode and tissue (Nightingale 1959); (5) *Sampling rate* (Jayne et al. 1990); (6) *Signal conditioning and temporal treatments*, including the use of filters and binning; (7) *Stimulus-types* presented to the subject; and (8) *Behavior* of the subject elicited by these stimuli. Some of these factors may or may not be trivial, and several have been treated in-depth elsewhere (see above). For the sake of brevity, here we focus on points 1, 2, 6, 7, and 8 below.

Among the most frequently used recruitment variables are (1) muscle activity amplitude, measured in mV and given as either a mean or a maximum of the strongest burst during a particular behavior; and (2) signal integrated area, a time-dependent intensity, measured in mV \times s. Both variable types are most commonly derived from the EMG signal after filtering and rectification.

Day of implant

Repeats of EMG implants or a positional shift of existing implants between experiments may result in differences in magnitude and intensity of recruitment. In order to compensate for these types of error, tests should be conducted to determine whether corrections of these two types of measurements are needed. For instance, such tests may involve parametric analyses using both corrected and uncorrected recruitment variables (Konow and Sanford 2008). While measurements of amplitude commonly require implant-correction, it is apparently not equally ubiquitous that integrated area measurements, being a function of both time and amplitude, will require such correction (Konow et al., manuscript in preparation). If needed, corrections can be carried out using either the maximum spike or the mean amplitude calculated from the strongest burst recorded for a given muscle during a particular implant. Additionally, the importance of implant accuracy, as emphasized in past analyses, prompts prior knowledge of muscle morphology, including any functional subdivisions and specializations of fiber type, implant practice on dead conspecifics, or alternatively, direct verification of electrode placement in specimens sacrificed after experimentation. Finally, a balanced statistical design should be adopted in order to factor the effect of implant (Wainwright et al. 1989).

Implant-position

The distance of a given electrode from the motor-endplate, and the intensity of a given behavior

(Herrel et al., 2008) will each affect the composition of signal types that are recorded. Evidence is currently emerging to suggest that muscles often possess regionally specialized fibers, either across deep and superficial fascia as commonly seen in the vertebrate *adductor mandibulae* muscle (German et al., 2008; Herrel et al., 2008), or functionally disparate segments of, for example, the *gastrocnemius* muscle (Higham et al. 2008). Decomposition of motor-unit activity patterns into groups of electrical signatures arising from single fibers or populations of physiologically similar motor-units, such as fast-twitch or slow twitch fibers, i.e., wavelet analysis, appears to be a powerful method of mitigating such amplitude-related errors in EMG analyses (von Tschärner 2000; Wakeling et al. 2006).

Signal conditioning

Since EMG signals contain frequency spectra of physiologically distinct motor-unit activity patterns (above), it follows that extreme care should be exercised when applying filters to EMG signals. It may alternatively be of merit to minimize the static and motion-related noise recorded in the raw signals, for instance by securing equipment in position, isolating electrode-wire links and encasing recording equipment in a Faraday cage.

Time-averaging, or binning of measurements of signal amplitude may sometimes reduce the variability that results from spikes in amplitude (German et al., 2008; Herrel et al., 2008), but is not always required (Konow et al., manuscript in preparation), as is also the case for integrated measurements of area (Konow and Sanford 2008). Regarding timing aspects of activity patterns of muscle, activity on-offset is frequently determined by eye-alignment, while the utility of less arbitrary criteria have been evaluated, including the use of two or three times the standard deviation of recruitment activity combined with a threshold duration of sustained activity (Hodges and Bui 1996; Roberts, manuscript in preparation).

Behavioral stimulus

When experimental treatments involve varied stimulation of EMG subjects, such as different hardness of prey or incline of the locomotor surface, the resultant behaviors may involve EMGs that are not directly spatiotemporally comparable (Wainwright and Friel 2000). Furthermore, such incomparability may result from differences in muscle activity that are not apparent in common graphic visualizations, such as EMG mean bar-plots. Both theoretical evaluations of the behaviors in terms of their functional comparability

(i.e., are the behaviors functionally homologous) and amplitude or duty-cycle corrections can be helpful tools in revealing such issues of EMG incomparability.

Behaviors elicited

When several different behaviors are elicited experimentally for comparing EMGs among them (Konow and Sanford 2008), it clearly becomes important that the entire behavioral suite under investigation is elicited during every experiment (implant-day). This approach serves to mitigate error related to recruitment level in the subsequent corrections of variables (Konow et al., manuscript in preparation).

Future directions

Papers in this issue illustrate that electromyography remains a powerful tool in integrative, functional morphological research, especially when combined with other techniques to gain a more comprehensive understanding of musculoskeletal function at multiple organizational levels. Based on roundtable discussions at the symposium, we propose three areas of priority for future EMG-based research.

First, studies of muscle performance need to be integrated with studies of neural mechanisms, as in a recent study of the role of proprioception in motor-pattern stereotypy in chewing (Ross et al. 2007). These areas have historically remained divided “at the neuromuscular junction” and their integration would improve our understanding of higher-level control of musculoskeletal systems. Motor control at the level of the neuron was a recommended area of focus arising from the 2001 symposium (*Amer Zool*, Vol. 41) and, as suggested here, still remains a priority for future studies.

Second, several important questions concern the degree of variation in EMGs at disparate levels. The level of variation in EMG that is most potent in causing functional change (Alfaro and Herrel 2001) has been a long-standing issue. As argued by Wainwright (2002; also in Alfaro and Herrel 2001), distinct changes in MAP ought to accompany musculoskeletal functional shifts that commonly are observed via analyses of skeletal kinematics using high-speed video or, more recently, using sonomicrometry. Examples of such MAP shifts, however, have only recently been detected and quantified (Konow and Sanford 2008). The high levels of motor-pattern plasticity argued in some earlier research (Wainwright 2002) correspond well with the observation that muscles are the dynamic components in musculoskeletal systems and therefore have to maintain the functional flexibility of the system. This variation may, however, potentially be distributed

across a wide range of factors, including structural (intrinsic) constraints, functional repertoire, and environmental (extrinsic) demands, both within and among individuals and taxa. Therefore, several relationships between structural, functional, behavioral, and environmental factors remain uncertain, including whether intrinsic musculoskeletal changes result directly from extrinsic factors and influence variation in intra-muscular activity. Hierarchical parametric analyses capable of segregating variation in EMG resulting from these factors will aid future research aiming to determine what levels of variation in EMG are most potent in driving functional changes.

Combination of EMG analyses with sonomicrometry and strain-gauge technology has helped explain musculoskeletal performance in several organisms and systems. Such synchronized integrative approaches will be useful in future examinations of several long-standing questions in muscle physiology, including whether mean amplitude and/or integrated area are appropriate proxy-measures of integrated production of force by muscles, and whether low-intensity EMG signals indicate inactivity in muscles or passive generation of force.

Third, a consensus on methodology, as suggested earlier, will be required for comparisons across a broad phylogenetic spectrum of homologous muscles performing biomechanically comparable tasks. Phylogenetically distant taxa (e.g., fish and mammals) may, in terms of kinematics, feed in very different manners but if the associated EMG data from functionally homologous muscles is analyzed in a comparable manner, it will be possible to achieve general comparisons of patterns of muscle activity. One way to further facilitate such comparisons in the future is to build an online database, analogous to Genbank or Morphbank, where EMG data are lodged with accession numbers in ASCII or other formats.

Acknowledgments

We would like to thank the Society for Integrative and Comparative Biology, the Division of Comparative Biomechanics, the *Journal of Experimental Biology*, AD Instruments, and Grass Technologies for their financial support of the Late-Breaking symposium on *Electromyography: Interpretation and limitations in functional analyses of musculoskeletal systems* at the 2008 annual SICB meeting. Discussions with Anthony Herrel, Peter Wainwright, Christopher Sanford, Cheryl Wilga, and Brad Moon motivated us to organize this symposium. We are especially grateful to the participants of the symposium for their contributions and efforts.

References

- Alfaro ME, Herrel A. 2001. Introduction: major issues of feeding motor control in vertebrates. *Am Zool* 41:1243–7.
- Alfaro ME, Janovetz J, Westneat MW. 2001. Motor control across trophic strategies: muscle activity of biting and suction feeding fishes. *Am Zool* 41:1266–79.
- Doty RW, Bosma JF. 1956. An electromyographic analysis of reflex deglutition. *J Neurophysiol* 19:44–60.
- German RZ, Crompton AW, Thexton AJ. 2008. Variation in EMG Activity: a hierarchical approach. *Integr Comp Biol*. doi: 10.1093/icb/icn022.
- Gerry SP, Ramsay JB, Dean MN, Wilga CD. 2008. Evolution of asynchronous paired muscle motor activity: effects of ecology, morphology and phylogeny. Proceedings of the Society for Integrative and Comparative Biology, January 2–6: in San Antonio, Texas. (<http://www.sicb.org/meetings/2008/schedule/>).
- Grubich JR. 2001. Prey capture in actinopterygian fishes: a review of suction feeding motor patterns with new evidence from an elopomorph fish, *Megalops atlanticus*. *Am Zool* 41:1258–65.
- Herrel A, Schaerlaeken V, Ross CF, Meyers J, Nishikawa K, Abdala V, Manzano A, Aerts P. 2008. Electromyography and the evolution of motor control: limitations and insights. *Integr Comp Biol*. doi: 10.1093/icb/icn025.
- Higham TE, Biewener AA, Wakeling JM. 2008. Functional diversification within and between muscle synergists during locomotion. *Biol Lett* 4:41–4.
- Hodges PW, Bui BH. 1996. A comparison of computer based methods for the determination of onset of muscle contraction using EMG. *Electroen Clin Neuro* 101:511–9.
- Jayne B, Bennett BC, Lauder GV. 1990. Muscle recruitment during terrestrial locomotion: how speed and temperature affect fiber type use in a lizard. *J Exp Biol* 154:101–28.
- Jayne B, Lauder GV. 1994. How swimming fish use slow and fast muscle fibers: implications for models of vertebrate muscle recruitment. *J Comp Phys A* 175:123–31.
- Konow N, Sanford CPJ. 2008. Is a convergently derived muscle-activity pattern driving novel raking behaviours in teleost fishes? *J Exp Biol* 211:989–99.
- Konow N, Camp AL, Sanford CPJ. 2008. Congruence between muscle activity and kinematics in a convergently derived prey-processing behaviour. Proceedings of the Society for Integrative and Comparative Biology, January 2–6: in San Antonio, Texas. (<http://www.sicb.org/meetings/2008/schedule/>).
- Loeb GE, Gans C. 1986. *Electromyography for experimentalists*. Chicago (IL): University of Chicago Press. p. 394.
- Motta PJ, Tricas TC, Hueter RE, Summers AP. 1997. Feeding mechanism and functional morphology of the jaws of the lemon shark *Negaprion brevirostris* (Chondrichthyes, Carcharhinidae). *J Exp Biol* 200:2765–80.
- Moyers RE. 1949. Temporomandibular muscle contraction patterns in angle class II, division 1 malocclusions: an electromyographic analysis. *Am J Orthod* 35:837–57.
- Nightingale A. 1959. Background noise in electromyography. *Phys Med Biol* 3:325–38.
- Roberts T, Gabaldon A. 2008. Interpreting muscle function from EMG: lessons learned from direct measurements of

- force. Proceedings of the Society for Integrative and Comparative Biology, January 2–6: in San Antonio, Texas. (<http://www.sicb.org/meetings/2008/schedule/>).
- Ross CF, Eckhardt A, Herrel A, Hylander WL, Metzger KA, Schaerlaeken V, Washington RL, Williams SH. 2007. Modulation of intra-oral processing in mammals and lepidosaurs. *Integr Comp Biol* 47:118–36.
- Sanford CPJ, Lauder GV. 1989. Functional morphology of the “Tongue-Bite” in the Osteoglossomorph fish *Notopterus*. *J Morph* 202:379–408.
- Shaffer HB, Lauder GV. 1985. Aquatic prey capture in aquatic salamanders: patterns of variation in muscle activity. *J Morph* 183:273–84.
- Thexton AJ, Crompton AW, German RZ. 2007. Electromyographic activity during the reflex pharyngeal swallow in the pig: Doty and Bosma (1956) revisited. *J Appl Physiol* 102:587–600.
- von Tscharner V. 2000. Intensity analysis in time–frequency space of surface myoelectric signals by wavelets of specified resolution. *J Electromyogr Kinesiol* 10:433–45.
- Wainwright PC. 2002. The evolution of feeding motor patterns in vertebrates. *Curr Opin Neurobiol* 12:691–5.
- Wainwright PC, Sanford CPJ, Reilly SM, Lauder GV. 1989. Evolution of motor patterns: aquatic feeding in salamanders and ray-finned fishes. *Brain Behav Evol* 34:324–41.
- Wainwright PC, Friel JP. 2000. Effects of prey type on motor pattern variance in tetraodontiform fishes. *J Exp Zool* 286:563–71.
- Wainwright PC, Richard BA. 1995. Scaling the feeding mechanism of the largemouth bass (*Micropterus salmoides*): motor pattern. *J Exp Biol* 198:1161–71.
- Wakeling JM, Uehli K, Rozitis AI. 2006. Muscle fibre recruitment can respond to the mechanics of the muscle contraction. *J R Soc Interface* 3:533–44.
- Westneat MW, Hall WG. 1992. Ontogeny of feeding motor patterns in infant rats: an electromyographic analysis of suckling and chewing. *Behav Neurosci* 106:539–54.