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Letter To The Editor

Reply to Farina and Enoka: The Reconstruct-and-Test Approach Is the Most Appropriate Validation for Surface EMG Signal Decomposition to Date

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REPLY: We thank Drs. Farina and Enoka for recognizing our surface electromyographic (sEMG) signal decomposition technology as being "impressive" and for appreciating that "the approach is far superior to even the most optimistic expectations in the field." We will use this opportunity to assuage doubts they and others might have, to correct their misunderstanding, and to expand on the advantages of our accuracy verification approach.

They begin by casting doubt on our algorithm's ability to resolve *N* overlapping action potentials in complex signal segments by relying on the notion that "global optimization of overlapping action potentials is a. . .NP-hard problem that cannot be solved by polynomial complexity algorithms." To those not versed in complexity theory, the jargon of NP-hard (nondeterministic polynomial time-hard) can create the mistaken impression that such problems are impossible to solve in any practical way unless *N* is small (say $N < 5$). Allowing for their NP-hard claim, which they assert but do not prove in their paper by Ge et al. (2010), it simply means that to correctly resolve *N* overlapping action potentials from *every* segment of a signal an algorithm must conduct a search among all possible overlaps for *some* of those segments. Importantly, this does not preclude the possibility that a polynomial–time search can correctly resolve almost all signal segments. As described in De Luca et al. (2006) and Nawab et al. (2010) this undertaking is made possible through the Artificial Intelligence based IPUS (integrated processing and understanding of signals) framework (Lesser et al. 1995). An example of a decomposition of nine overlapping action potentials is provided in Fig. 12 in Nawab et al. (2010), a study Drs. Farina and Enoka cite. The high accuracy of our test (reported as 92.0% on average, but with recent improvements it is >95.2% on average) is an empirical validation that for relatively large values of *N*, a great preponderance of segments in real sEMG signals can be resolved correctly.

They proceed to question the accuracy assessments we reported for our algorithm. They make four claims, each of which shows a major misunderstanding of our reconstruct-and-test approach.

Claim 1. ". . .we propose that De Luca and Hostage decompose a set of synthetic surface EMG signals that we generate with a model and for which we know the discharge times of all the involved motor units."

REBUTTAL. Although it is stated clearly in Nawab et al. (2010) and De Luca and Hostage (2010), they miss the point that our reconstructed signals are indeed *synthetic surface EMG signals* for which *we know* the *action potential shapes* and the *firing times* of *all* involved motor units throughout the signal (see Fig. 9 in Nawab et al. 2010). Each of our synthetic signals often consists of >500 action potentials/s. Given that each action potential is 5 to 10 ms long, these synthesized signals contain many segments in which numerous action potentials overlap. The fact that our algorithm is able to correctly resolve >95% of the firing times and action potential shapes of 20 to 40 (recently increased to >60) motor units from such synthesized signals should allay any concerns of reasonable and unbiased observers.

Claim 2. "A disagreement in the results of the two decomposition methods is biased toward discharges detected by the first decomposition [real signal] and not by the second [reconstructed signal], whereas there were no converse cases of discharges detected by the second decomposition and not by the first (their Fig. 10)."

REBUTTAL. This claim is based on a false conjecture. As indicated in the caption, Fig. 10 is intended to show a comparison of the firing instances of the two decompositions. It is not described as a documentation of the false positives and the false negatives. Some, but not all, of the missed firings are indicated by a circle. For example the seventh firing of MU #17 has an unidentified missed firing. Also the fourth and eighth firings of MU #1 have false positives. We found that false positives are as frequent as false negatives. That is why both false positives and false negatives are used in the accuracy criterion reported in Nawab et al. (2010) and used by De Luca and Hostage (2010).

Claim 3. "Low power in the residual signal results in the algorithm being applied to two signals that are almost identical. . .so that their decompositions will be necessarily very similar, which is incorrectly associated to high accuracy."

REBUTTAL. Not all residual signals have low power. As in Claim 1, they make generalizations from singular examples rather than appreciating the generality of the concepts described. Let us examine the extreme case they suggested, where the decomposition by our algorithm of a real sEMG signal into *N* action potential trains produces a residual signal that is zero for all time. If so, the entire sEMG signal would be modeled *perfectly* as the superposition of shifted and overlapped *N* distinct action potential shapes estimated from the action potentials found in the same sEMG signal. If so, the overlapped action potentials have been optimally resolved everywhere in the sEMG signal. It is therefore reasonable to conclude that the decomposition is 100% accurate and that is exactly what our reconstruct-and-test procedure would do in such a situation.

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Claim 4. "The decomposition method. . .has not been validated systematically with approaches other than the reconstruct-and-test procedure."

REBUTTAL. Nonetheless they acknowledge that De Luca et al. (2006) validated the algorithms with the two-source test (Mambrito and De Luca 1984). When comparing decompositions of indwelling electromyographic (iEMG) to sEMG signals we reported an accuracy of ≤97.6%. We compared, but did not report, decompositions from 13 contractions in the FDI and found an average accuracy of 94.3 ± 1.9%. Later, Nawab et al. (2010) compared decompositions of two sEMG signals and found an accuracy of 92%.

The two-source test compares all firings of motor units that are found to be in common with the decomposed signal from each sensor. It has two deficiencies. First, as stated in Nawab et al. (2010), it compares the firings of only a small subset (3 to 5) of the in-common motor unit trains detected by both sensors. It provides no information on the accuracy of the remainder of the decomposed motor unit trains. Second, when comparing decompositions of iEMG and sEMG signals, different algorithms are required for each; thus some errors may be due to the iEMG signal decomposition rather than the sEMG signal decomposition.

The mathematically synthesized signal test has at least three flaws. First, it is a *generic test* used under artificial circumstances. It does not directly test the decomposition accuracy of a real EMG signal. It requires the presumption that the accuracy results obtained under artificial conditions faithfully represent the decomposition accuracy of a real EMG signal. Second, it is subjective. The ascribed firing rates are assigned by choice. Third, it does not consider the changing shape of the action potentials that occur in the sEMG signal due to gradual movements of the muscle fibers with respect to the electrodes, as commonly occurs during force increasing isometric contractions; or the more abruptly changing shapes and firing rates during erratic force fluctuations; or the gradually changing shapes due to fatiguing processes; or the awkward shapes due to muscle fiber injury or disease, among other confounding factors. Any test for accuracy must be subjected to these foibles rather than well-behaved mathematically synthesized shapes.

The reconstruct-and-test approach was developed to overcome the shortcomings of the generic mathematically synthesized signal test and the two-source test. It is a *specific test*. It may be used individually on every decomposed real sEMG signal to establish the accuracy of the firings of *each motor unit*. This enables the user to focus on the more accurate data. A generic test cannot provide this distinction of practical importance. Users familiar with decomposition technologies know that the decomposition accuracy is influenced by the signal-to-noise ratio of a *collected sEMG signal*, which in turn depends on the quality of electrical contact between the skin and the electrodes and the location of the sensor on the muscle. Thus a generic test will not provide the degree of accuracy for a specific contraction performed on a specific subject on a specific day. Knowing how well a decomposition algorithm functions under artificial test conditions provides no assurance that it works well on a specific real EMG signal, whereas our test does.

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