Vaz, J. R., Olstad, B. H., Cabri, J. M. H., Kjendlie, P.-L., Pezarat Correia, P., Hug, F. (2016). Muscle coordination during breaststroke swimming: Comparison between elite swimmers and beginners. *Journal of Sports Sciences, 34, 1941-1948*.

Title: **Muscle coordination during breaststroke swimming: comparison between elite swimmers and beginners**

Running head: Muscle coordination in breaststroke swimming

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Abstract

The present study aimed to compare muscle coordination strategies of the upper and lower limb muscles between beginners and elite breaststroke swimmers. Surface electromyography of eight muscles was recorded in 16 swimmers (eight elite, eight beginners) during a 25m swimming breaststroke at 100 % of maximal effort. A decomposition algorithm was used to identify the muscle synergies that represent the temporal and spatial organization of muscle coordination. Between-groups indices of similarity and lag times were calculated. Individual EMG patterns were moderately to highly similar between groups (between-group indices range: 0.61 to 0.84). Significant differences were found in terms of lag time for pectoralis major ($p < 0.05$), biceps brachii, rectus femoris and tibialis anterior ($p < 0.01$), indicating an earlier activation for these muscles in beginners compared to elites (range: -13.2 to -3.8 % of the swimming cycle). Three muscle synergies were identified for both beginners and elites. Although their composition was similar between populations, the third synergy exhibited a high within-group variability. Moderate to high indices of similarity were found for the shape of synergy activation coefficients (range: 0.63 to 0.88) but there was a significant backward shift (-8.4 % of the swimming cycle) in synergy #2 for beginners compared to elites. This time shift suggested differences in the global arm-to-leg coordination. These results indicate that the synergistic organization of muscle coordination during breaststroke swimming is not profoundly affected by expertise. However, specific timing adjustments were observed between lower and upper limbs.

Keywords (4-6 words)

1.Swimming; 2.Muscle Synergies; 3.Electromyography; 4.Expertise; 5.Coordination;

Introduction

During breaststroke swimming, there is a large intra-cyclic velocity variation (Holmér, 1979; Schnitzler, Seifert, Ernwein, & Chollet, 2008) of the body's center of mass (Leblanc, Seifert, Tourny-Chollet, & Chollet, 2007; Takagi, Sugimoto, Nishijima, & Wilson, 2004). It makes this swimming stroke the slowest among the four competitive strokes (Craig, Skehan, Pawelczyk, & Boomer, 1985). One of the key determinants for the performance is the ability of the swimmer to efficiently coordinate the upper and lower limbs, particularly during the non-propulsive/recovery phases (Komar, Sanders, Chollet, & Seifert, 2014). Therefore, comprehensive information about coordination strategies during breaststroke swimming may benefit athletes and coaches.

Muscle coordination during breaststroke swimming has initially been studied in the 1960'-80's (Ikai, Ishii, & Miyashita, 1964; Lewillie, 1973; 1974; Nuber, Jobe, Perry, Moynes, & Antonelli, 1986; Yoshizawa, Tokuyama, Okamoto, & Kumamoto, 1976). These studies focused on the qualitative description of raw myoelectrical signals measured using electromyography (EMG) making it difficult to compare individuals. This is confirmed by a recent systematic review, which concluded that most of the EMG studies that focus on muscle coordination during swimming present significant methodological issues (Martens, Figueiredo, & Daly, 2015).

In addition, despite the importance of the kicking action in breaststroke (Vilas-Boas, 1994) there is a lack of information on lower limb muscle activation patterns and therefore on the coordination between upper and lower limb muscles. Finally, the comparison between elite and beginners is scarce. Although there is no effect of expertise on muscle coordination during basic motor tasks such as rowing (Turpin, Guével, Durand, & Hug, 2011) or bench press (Kristiansen, Madeleine, Hansen, & Samani, 2013), it is unclear whether a more complex motor task such as breaststroke is associated with different muscle coordination strategies between beginners and elite swimmers.

This study aimed to compare muscle coordination strategies of the upper and lower limbs between beginners and elite swimmers. Muscle coordination was described with consideration to both individual EMG patterns and muscle synergies. Muscle synergies are defined as a group of muscles activated in synchrony. They have been shown to be associated with functional subtasks during motor tasks such as gait (van den Hoorn, Hodges, van Dieën, & Hug, 2015), pedaling (Hug, Turpin, Guével, & Dorel, 2010) and rowing (Turpin et al., 2011). Therefore, they can describe muscle coordination strategies in a more integrative fashion. Based on previous studies performed less complex motor tasks, we hypothesized that the individual EMG patterns would be similar, but that a time-shift would exist between elite and beginners as previously reported from kinematics during arm-to-leg coordination tasks (Leblanc, Seifert, & Chollet, 2009; Seifert, Leblanc, Chollet, & Delignières, 2010; Takagi et al., 2004).

Methods

Participants

Sixteen swimmers (8 beginners [4 males and 4 females, age 11.6 ± 1.2 yrs] and 8 elites [4 males and 4 females, age 23.7 ± 7.4 yrs]) participated in this study. At the time of this study, their personal best time was 51.03 ± 6.12 s in the 50m breaststroke short course (i.e. 53.6 ± 7.6 % of the World Record) and 30.83 ± 2.99 s (i.e. 88.0 ± 4.7 % of the World Record) for beginners and elites, respectively. Beginners used to practice 2 to 3 times a week (about 3 to 5 hours/week which represents a swimming distance of approximately 6000 m/week) and elites 8 to 12 times a week (about 16 to 25 hours/week which represents approximately 80000 meters/week). Participants and their legal representative (when required) provided informed written consent. The Regional Committee for Medical and Health Research Ethics approved the experiment (2010/2893a) and all procedures adhered to the Declaration of Helsinki.

Materials and data collection

Experiments were conducted in a 25 m indoor pool with water temperature of approximately 29 ºC. After a 15 min warm-up with low- to moderate-intensity aerobic swimming and elements of kicking and drill exercises, participants performed 25 m breaststroke at 100% of maximal effort. Participants started swimming in the water with a push off from the wall. Borg Rate of Perceived Exertion (RPE) was used to assess the effort level (Borg, 1998).

A five-underwater-camera system (Qualysis, Gothenburg, Sweden) was used and placed at the same side of the pool. Markers were attached to the skin on the right iliac crest, trochanter major, lateral part of the thigh, lateral femoral condyle, shank, the most posterior part of calcaneus, medial and lateral malleolus, and 1st and 5th metatarsals. Movement data were sampled at 100 samples/s.

Myoelectrical activity (EMG) was recorded from 8 muscles on the right side of the body: triceps brachii (TB), biceps brachii (BB), lower trapezius (LT), pectoralis major (PM), gastrocnemius medialis (GM), tibialis anterior (TA), long head of biceps femoris (BF) and rectus femoris (RF). These muscles were selected such that we could study pairs of agonist-antagonist muscles. In addition, they have been identified as key muscles for breaststroke swimming (Martens et al., 2015; McLeod, 2010; Ruwe, Pink, Jobe, Perry, & Scovazzo, 1994).

Prior to the electrode placement, the skin was shaved and cleaned with an alcohol solution to minimize skin impedance. Disposable pre-gelled Ag/AgCl waterproof triode electrodes (recording zone: 10 mm diameter) with inter-electrode distance of 20 mm (Plux, Lisbon, Portugal) were placed according to SENIAM (Surface EMG for Non-Invasive Assessment of Muscles) Project recommendations (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). Two self-adhesive foams (Multi Bio Sensors In., El Paso, TX, USA) were glued together by the manufacturer forming a tight seal around the snap. The large contact surface of the electrodes with pre glued and silicon covers on the snap created a waterproof seal between the electrode and the participant’s skin. The amplifier was embedded in silicon material to sustain waterproof. The wires were securely fixed to avoid movement artifacts. This configuration to record underwater EMG signals has been shown to be reliable (Olstad, Zinner, Cabri, & Kjendlie, 2014).

EMG signals were acquired using a telemetric system (Plux, Lisbon, Portugal) according to the recommendations from the International Society of Electrophysiology and Kinesiology (ISEK) (Merletti & Di Torino, 1999): input impedance > 100 MΩ, common mode rejection ratio was 110 dB, amplified with a gain of 1000, band-pass filtered (10-500 Hz) and digitized at 1000 samples/s.

A swimming cycle consisted of two phases: lower limb propulsive and recovery phase. The propulsive phase was considered to be the period from maximal knee flexion until the beginning of knee flexion after gliding; and the recovery phase was set as from beginning of knee flexion until the next maximal knee flexion angle. As beginners and elite swimmers may show different relative time phases, each phase was time normalized such that each represents 50% of a swimming cycle.

EMG pre-processing

Raw EMG signals were processed according to the recommendations from the International Society of Electrophysiology and Kinesiology (Merletti & Di Torino, 1999): band-pass filtered (20-500 Hz), full-wave rectified and smoothed with a low pass filter (12 Hz, 4th order Butterworth). Based on visual inspection, a section of EMG containing at least 4 cycles (mean: 7.8 ± 3.4; range: 4-10) without movement artifacts was selected for further analysis. Each phase was interpolated to 100 points and normalized to the peak EMG value across the selected cycles. Therefore, as classically done in studies focusing on muscle synergies, the degree of muscle activation was not considered. This choice was motivated by the fact that there is no consensus on the best normalization technique for dynamic tasks (Hug, 2011).

Extraction of muscle synergies

A Nonnegative Matrix Factorization (NMF) was performed to extract muscle synergies. We implemented the Lee & Seung (2001) algorithm. Matrix factorization minimizes the residual Frobenius norm between the initial matrix and its decomposition, given as

$$\mathrm{E} = \mathrm{WC} + \mathrm{e}$$
$$\min_{\substack{\mathrm{W}\geq 0\\ \mathrm{C}\geq 0}} ||\mathrm{E} - \mathrm{WC}||_{\mathrm{FRO}}$$

where E is a p-by-n initial matrix (p = number of muscles and n = number of time points), W is a p-by-s (s = number of synergies), C is an s-by-n matrix and e is a p-by-n matrix. $||\cdot||_{FRO}$ establishes the Frobenius norm and e is the residual error matrix. This decomposition algorithm comprises two components: the *muscle synergy vectors* (W) which represent the relative weighting of each muscle within each synergy and, the *synergy activation coefficient* (C), which represents the relative activation of the muscle synergy across the swimming cycles. The algorithm was repeated 10 times.

The initial matrix E consisted of 4 to 10 cycles. E was therefore an 8 row by 800 to 2000 columns matrix. Total Variance Accounted For (VAF) was calculated as previously described (Frère & Hug, 2012). We iterated the analysis by varying the number of synergies between 1 and 8 (i.e. number of muscles recorded). Then we selected the least number of synergies that accounted for > 90% of the Total Variance Accounted For or until adding an additional synergy did not increase VAF by > 5% of the Total Variance Accounted For (Clark, Ting, Zajac, Neptune, & Kautz, 2010).

Assessment of within and between-group similarity

Differences in individual EMG patterns and synergy activation coefficients were assessed through lag time and $r_{\max}$ coefficient. The lag time enables the assessment of differences in timing of activation (i.e., the magnitude of the time-shift between waveforms) and was determined as the lag time at the maximum of the cross-correlation function obtained using the Matlab (2012b, Mathworks Inc., Natick Massachusetts, USA) *xcorr* function for centered data (option “coeff”). $r_{\max}$ corresponds to the correlation coefficient at this maximum and gives an indication of the waveforms’ similarity (i.e. the shape of the patterns). As performed in previous studies $r_{\max}$ statistics were based on Z-transformed values (Turpin et al., 2011). The lag time and $r_{\max}$ were calculated for each pair of elite-beginners. By averaging the $r_{\max}$-values of all elite-beginner pairwise (i.e., 64 [8 elite x 8 beginners]) the index of between-group variability was determined. These have previously been used as indicators of the waveform consistency between and within populations (Ivanenko, Cappellini, Dominici, Poppele, & Lacquaniti, 2005; Turpin et al., 2011).

To further assess the similarity of the muscle synergies between elite and beginners, we checked that the muscle synergies extracted from the beginners accounted for the EMG patterns of each beginner and elite swimmer. To do this, the synergy vectors matrix ($W_{\text{beginners}}$) extracted from the entire population of beginners was held fixed in the Nonnegative Matrix Factorization algorithm while the activation coefficient matrix of the compared subject (C_{subject}) was free to vary (Hug et al., 2010). C_{subject} was initialized with random values and iteratively updated until convergence. The EMG data matrix of the compared subject (E_{subject}) was provided to the algorithm with the following update rule (Lee and Seung, 2001):

$$(C_{subject})_{ij} \leftarrow (C_{subject})_{ij} \frac{(W_{control}\, E_{subject})_{ij}}{(W_{control}\, W_{control}\, C_{subject}\,)_{ij}}$$

Note that when the compared subject was a beginner, they were not taken into account in the calculation of the synergy vector matrix for the beginners group, i.e., the initial matrix was composed by 7 (8-1) beginners. Sixteen pairwise comparisons (8 for beginners and 8 for elite participants) were performed. The overall VAF was used to quantify the accuracy of the reconstructed individual EMG patterns using the fixed muscle weightings and the newly computed synergy activation coefficients.

Statistical Analysis

Normality was verified through the Shapiro-Wilk normality test (SPSS version 21.0, SPSS Inc., Chicago, IL, USA). All data are reported as mean ± standard deviation. A significance level of $p < 0.05$ was used.

To evaluate the between-group differences in the time lag, a sample Student's t-tests with zero as reference value was performed. VAF values were compared between groups using a sample Student's t-test. When normality was not assumed, One-Sample Wilcoxon Signed Rank Test was used.

Results

Individual EMG patterns

All participants rated > 19 (out of 20) on the Borg scale allowing us to consider that they produced a maximal effort. The individual EMG patterns for each muscle and each population are depicted in Figure 1. The between-group index of similarity (i.e. $r_{\max}$) averaged across all muscles was 0.71 ± 0.08. The highest between-group index of similarity was found for rectus femoris ($r_{\max} = 0.84 \pm 0.11$) while the triceps brachii exhibited the lowest between-group similarity ($r_{\max} = 0.61 \pm 0.15$) (Table1). Of note, $r_{\max}$ considers the shape of the EMG patterns without consideration of possible time shift.

When considering the lag time, a significant negative shift was observed in four muscles (pectoralis major, biceps brachii, rectus femoris and tibialis anterior) in beginners compared to elite swimmers (Table 1). It means that these muscles were activated earlier (range: -13.2 to -3.8 % of the swimming cycle) during the cycle in beginners compared to elites.

Muscle Synergies

Using the previously described criteria, 3 synergies were identified in 13 of the 16 (81%) swimmers. The remaining swimmers (1 beginner, 2 elites) exhibited four synergies. To facilitate the comparison of the set of synergies between participants, 3 muscle synergies were extracted for all participants. The three-extracted muscle synergies accounted for a similar VAF between elite swimmers (87.9 ± 2.9%) and beginners (88.0 ± 1.9%; $p = 0.921$). Synergy #1 mainly involves the lower limb muscles (rectus femoris, biceps femoris, gastrocnemius medialis and tibialis anterior) and lower trapezius, and is activated during the kicking phase (lower limb propulsive phase) (Figure 2). Synergy #2 mainly involves upper limb muscles (particularly pectoralis major and biceps brachii) and is activated during the lower limb recovery phase (Figure 2). Synergy #3 is highly variable between participants and detailed inspection of this synergy enabled the identification of three main patterns (Figure 3), regardless of the level of expertise.

Cross validation of muscle synergies

The similarity of the muscle synergies between the two populations was assessed using the muscle synergy vectors extracted from beginners (from a dataset merging all the beginners) to reconstruct the EMG patterns of each participant. Muscle synergy vectors of the beginners' population explained in averaged 84.2 ± 2.6% of VAF for beginners and 80.2 ± 5.3% of VAF for elite swimmers ($p = 0.072$). It means that the difference between populations was not significantly higher than the variability within the beginners. Inspection of individual data indicates that 3 out of the 8 (37.5%) elite swimmers showed VAF value < 80% (range: 71.6 – 78.7%), a threshold that have been used by other authors to determine the correct number of synergies (van den Hoorn et al., 2015). Interestingly, the two elite swimmers with the lowest VAF values (the most different from the beginners population) were among the top three swimmers of this experiment in terms of % of the World Record. Note that all the beginners exhibited VAF value > 80%.

Between-group similarity of activation coefficients (C)

The between-group indices of similarity for activation coefficients were 0.88 ± 0.09, 0.84 ± 0.12 and 0.63 ± 0.13 for synergy #1, #2 and #3, respectively. Regarding the lag time (Table 1), a significant negative shift (- 8.4 %) was observed in synergy #2 ($p < 0.001$) in beginners compared to elite.

Discussion

The aim of this study was to compare muscle coordination of the upper and lower limb between beginners and elite breaststroke swimmers. The synergistic organization of muscle coordination was not profoundly affected by the expertise. However, specific timing adjustments in their activation were observed, especially for synergy #2. In addition, although the shape of the individual EMG patterns were moderately to highly similar between groups, time shifts were found for pectoralis major, biceps brachii, rectus femoris and tibialis anterior muscles. It indicates that swimming expertise is associated to changes in the temporal rather than the spatial structure of muscle coordination.

Similar EMG patterns have been reported between untrained and trained athletes during rowing (Turpin et al., 2011) and bench press (Kristiansen et al., 2013), which can be considered as less complex motor tasks than breaststroke swimming. Because breaststroke swimming involves numerous degrees of freedom from both upper and lower limbs, many different motor coordination strategies are available to successfully perform the task. As such, a profound change in muscle coordination with expertise was possible but not observed. Instead, we observed subtle changes in the temporal structure of coordination that could have a major impact in the overall performance.

A time-shift (i.e. the lag time) between elite and beginners patterns can evidence changes in the temporal organization of muscle patterns and ultimately can provide relevant information in terms of inter-limb coordination. Previous studies that focused on limb coordination during breaststroke reported differences in arm-to-leg coordination timings between elite and non-elite breaststrokers (Komar et al., 2014; Leblanc, Seifert, Baudry, & Chollet, 2005; Takagi et al., 2004). Interestingly, the significant differences in lag time were observed for the muscles with higher between-group index of similarity (pectoralis major, biceps brachii, rectus femoris and tibialis anterior). All these four muscles showed a statistically significant backward shift in beginners compared to elites. The beginners activated the rectus femoris muscle earlier than the elites. It might indicate that beginners also activate rectus femoris as a hip flexor close to the end of the lower limb recovery phase (Figure 1). This hip flexion at the end of leg recovery is commonly reported in beginners and explained as an inability to keep the hip straight-lined with trunk to decrease drag. Another usual technical feature in beginners is the inefficient timing of ankle dorsiflexion during leg recovery. This inefficient timing (i.e., too early dorsiflexion) increases drag, and therefore decreases swimming velocity. This is supported here by the observed earlier shift in tibialis anterior timing found in beginners compared to elites. Time-shifts observed for pectoralis major and biceps brachii muscles are likely to be related with differences in arm-to-leg coordination strategy. Although beginners and elites extend their arms at the same period of the stroke cycle, beginners are unable to keep the arms extended (i.e., a straight-lined position) and begin arm flexion (i.e., upper limb propulsive phase) earlier than the elite (Seifert et al., 2010). This shows an ineffective coordination pattern as beginners do not take advantage of the kicking phase, but instead increase the drag. In contrast, the elite were able to keep a straight-lined position by gliding with the arms extended.

Muscle synergy analysis has the potential to give a global picture of the muscle coordination strategies (Hug, 2011). Overall, the two populations exhibited the same number of muscle synergies suggesting a similar complexity of motor control between beginners and elites. Synergy activation coefficients were similar between groups for both synergy #1 and #2. However, synergy #3 was more variable among individuals, regardless the level of expertise. Breaststroke swimming enables the use of different motor options to achieve the same goal. Thus, this can explain the variability found in synergy #3 within both populations (Figure 3).

Although the level of similarity was high for synergies #1 and #2, a significant backward shift was observed in beginners compared with elites for synergy #2. This synergy is composed by upper limb muscles and may reflect the arm-to-leg coordination differences reported in previous studies (Leblanc et al., 2005; 2009; Seifert et al., 2010; Seifert et al., 2011), i.e. beginners tend to begin the arm propulsion before the elite (Seifert et al., 2010). It is important to note that time-shift found for synergy #2 can lead to erroneous conclusions due to the time normalization procedure that used the lower limb events as reference. If the swimming cycle had been time-normalized based on upper limb events, it is likely that the time shift would have been found for synergy #1 rather than synergy #2. This means that these results should be interpreted in regards to our specific time-normalization procedure, i.e. as differences in arm-to-leg coordination. Although Seifert et al. (2010) showed that arm-to-leg coordination differs between beginners and elites (particularly in regards to the ability to keep the arms straight), the absence of kinematics data did not allow us to verify this observation in our populations of swimmers.

In contrast to Synergy #1 and #2, synergy #3 was different among swimmers such that regardless the expertise level, synergy #3 represented different functional roles among swimmers. Although the most frequently observed synergy (Fig. 3, upper panels) involves upper limb muscles (pectoralis major and triceps brachii) during the recovery phase, synergy #3 involves lower limb muscles during the kicking phase in other swimmers. It is important to keep in mind that this third synergy explained less than 7.3 ± 1.7% of VAF, suggesting that its role in muscle coordination during swimming is much less than that of Synergy #1 and #2. The impact of synergy #3 in swimming performance remains to be determined.

Our EMG results are in accordance with previously reported kinematics data. Although elite athletes show an ‘opposition’ or ‘continuity’ pattern of inter-limb coordination (i.e., the upper and lower limbs are mostly in an anti-phase pattern and in-phase pattern during gliding) in order to take advantage of limbs propulsion and minimize active drag, beginners mostly show a ‘superposition’ pattern (i.e., an overlap of lower and upper limb propulsion phases, which represents a in-phase pattern during propulsion phases as well) (Seifert et al., 2010). This is evident in our results as beginners exhibited a backward time-shift of synergy #2 (i.e. upper limb) and the inter-limb coordination tended to a ‘superposition’ pattern as the gap between lower limb and upper limb actions was smaller. In other words, elite swimmers effectively reduce the drag and hence take more advantage of the propulsive forces through their arm-to-leg coordination (Leblanc et al., 2005) and by being able to keep the limbs properly extended during gliding (Komar et al., 2014). Using EMG, our study provides a deeper understanding on the origin of this difference in kinematics. More precisely, the fact that both populations exhibit the same number of muscle synergies and a similar composition of the two main synergies (#1 and #2) suggests that they used similar neural control strategies. Differences in kinematics reported in previous works are likely explained by timing adjustments of some muscles/synergies. Similar results have been observed during pedaling across different mechanical constraints where muscle synergies were preserved across the conditions, despite slight adaptations in their activation timing were observed (Hug et al., 2011).

The present study has some limitations. Beginners were at different levels of the learning process (e.g., while some may had just began to apply Newton’s third law, others may had already began to exploit aquatic resistances: distinguish propulsion, recovery, acceleration and glide) (Seifert et al., 2011). Beginners also have a lower training load compared to elites, which may influence muscular activity (e.g., resistance to fatigue). However, the training load is a group feature that increases as the swimmers gets more expert. The age difference between elite and beginners may be seen as another limitation, as the two populations were likely at different stages of maturity. Therefore we cannot definitely address whether our results are the consequence of maturity or expertise, or both. Further studies are needed to isolate the effect of maturity or expertise on muscle coordination. However, we believe that it did not deeply affect our results since similar differences in inter-limb coordination patterns as been shown between elite and beginners of the same age (Leblanc et al., 2005; 2009; Seifert et al., 2010).

Inspection of sample's FINA points confirmed that the beginners were more heterogeneous than the elites in terms of performance. Further investigations are needed to study populations with similar levels of within-group variability in terms of performance.

Conclusion

The global synergistic organization of muscle coordination in breaststroke swimming is not profoundly affected by expertise. However, differences in the timing of activation of the two main synergies were observed between beginners and elite swimmers. As these two synergies reflect the upper and lower limbs, it is likely that this inter-limb coordination is a key determinant of breaststroke performance. It suggests that coaches and athletes should focus their training sessions on optimizing temporal aspects of the inter-limb coordination. A follow-up study of the beginners' population may help to understand how this coordination strategy is modified over time to match that of the elites.

References

Borg, G. (1998). Borg's perceived exertion and pain scales. Champaign, IL, US: Human Kinetics.

Clark, D. J., Ting, L. H., Zajac, F. E., Neptune, R. R., & Kautz, S. A. (2010). Merging of Healthy Motor Modules Predicts Reduced Locomotor Performance and Muscle Coordination Complexity Post-Stroke. *Journal of Neurophysiology*, *103*(2), 844–857. http://doi.org/10.1152/jn.00825.2009

Craig, A. B., Skehan, P. L., Pawelczyk, J. A., & Boomer, W. L. (1985). Velocity, Stroke Rate, and Distance Per Stroke During Elite Swimming Competition. *Medicine & Science in Sports & Exercise*, *17*(6), 625–634.

Frère, J., & Hug, F. (2012). Between-subject variability of muscle synergies during a complex motor skill. *Frontiers in Computational Neuroscience*, *6*, 99. http://doi.org/10.3389/fncom.2012.00099

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology*, *10*(5), 361–374.

Holmér, I. (1979). Analysis of acceleration as a measure of swimming proficiency. In J. Terauds & E. Bedingfield (Eds.), *Biomechanics and Medicine In Swimming III* (pp. 119–125). Champaign, Illinois: Biomechanics and Medicine in Swimming III.

Hug, F. (2011). Can muscle coordination be precisely studied by surface electromyography? *Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology*, *21*(1), 1–12. http://doi.org/10.1016/j.jelekin.2010.08.009

Hug, F., Turpin, N. A., Guével, A., & Dorel, S. (2010). Is interindividual variability of EMG patterns in trained cyclists related to different muscle synergies? *Journal of Applied Physiology (Bethesda, Md. : 1985)*, *108*(6), 1727–1736. http://doi.org/10.1152/japplphysiol.01305.2009

Ikai, M., Ishii, K., & Miyashita, M. (1964). An Electromyographic Study of Swimming. *Research of Physical Education*, *7*(4), 47–54.

Ivanenko, Y. P., Cappellini, G., Dominici, N., Poppele, R. E., & Lacquaniti, F. (2005). Coordination of locomotion with voluntary movements in humans. *Journal of Neuroscience*, *25*(31), 7238–7253. http://doi.org/10.1523/JNEUROSCI.1327-05.2005

Komar, J., Sanders, R. H., Chollet, D., & Seifert, L. (2014). Do Qualitative Changes in Interlimb Coordination Lead to Effectiveness of Aquatic Locomotion Rather Than Efficiency? *Journal of Applied Biomechanics*, *30*(2), 189–197. http://doi.org/10.1123/jab.2013-0073

Kristiansen, M., Madeleine, P., Hansen, E. A., & Samani, A. (2013). Inter-subject variability of muscle synergies during bench press in power lifters and untrained individuals. *Scandinavian Journal of Medicine & Science in Sports*, n/a–n/a. http://doi.org/10.1111/sms.12167

Leblanc, H., Seifert, L., & Chollet, D. (2009). Arm–leg coordination in recreational and competitive breaststroke swimmers. *Journal of Science and Medicine in Sport*, *12*(3), 352–356. http://doi.org/10.1016/j.jsams.2008.01.001

Leblanc, H., Seifert, L., Baudry, L., & Chollet, D. (2005). Arm-Leg Coordination in Flat Breaststroke: A Comparative Study Between Elite and Non-Elite Swimmers. *International Journal of Sports Medicine*, *26*(9), 787–797. http://doi.org/10.1055/s-2004-830492

Leblanc, H., Seifert, L., Tourny-Chollet, C., & Chollet, D. (2007). Intra-cyclic Distance per Stroke Phase, Velocity Fluctuations and Acceleration Time Ratio of a Breaststroker's Hip: A Comparison between Elite and Nonelite Swimmers at Different Race Paces. *International Journal of Sports Medicine*, *28*(2), 140–147. http://doi.org/10.1055/s-2006-924205

Lee, D. D., & Seung, H. S. (2001). Algorithms for non-negative matrix factorization. In *Advances in neural information processing systems* (pp. 556–562). Cambridge.

Lewillie, L. (1973). Muscular activity in swimming. In S. Cerquiglini, A. Venerando, & J. Wartenweiler (Eds.), *Biomechanics III* (pp. 440–445). Basel, Switzerland.

Lewillie, L. (1974). Telemetry of electromyographic and electrogoniometric signals in swimming. In R. C. Nelson & C. A. Morehouse (Eds.), *Biomechanics IV* (pp. 203–207). Baltimore, Maryland, USA: University Park Press.

Martens, J., Figueiredo, P., & Daly, D. (2015). Electromyography in the four competitive swimming strokes: A systematic review. *Journal of Electromyography and Kinesiology*, *25*(2), 273–291. http://doi.org/10.1016/j.jelekin.2014.12.003

McLeod, I. (2010). Swimming anatomy. Human Kinetics.

Merletti, R., & Di Torino, P. (1999). Standards for reporting EMG data. *Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology*, *9*(1), 3–4.

Nuber, G. W., Jobe, F. W., Perry, J., Moynes, D. R., & Antonelli, D. (1986). Fine wire electromyography analysis of muscles of the shoulder during swimming. *The American Journal of Sports Medicine*, *14*(1), 7–11.

Olstad, B. H., Zinner, C., Cabri, J., & Kjendlie, P.-L. (2014). Surface electromyographic measurements on land prior to and after 90 min of submersion (swimming) are highly reliable. *Journal of Electromyography and Kinesiology :*

Official Journal of the International Society of Electrophysiological Kinesiology, *24*(5), 698–703. http://doi.org/10.1016/j.jelekin.2014.06.006

Ruwe, P. A., Pink, M., Jobe, F. W., Perry, J., & Scovazzo, M. L. (1994). The normal and the painful shoulders during the breaststroke. Electromyographic and cinematographic analysis of twelve muscles. *The American Journal of Sports Medicine*, *22*(6), 789–796.

Schnitzler, C., Seifert, L., Ernwein, V., & Chollet, D. (2008). Arm coordination adaptations assessment in swimming. *International Journal of Sports Medicine*, *29*(6), 480–486. http://doi.org/10.1055/s-2007-989235

Seifert, L., Leblanc, H., Chollet, D., & Delignières, D. (2010). Inter-limb coordination in swimming: Effect of speed and skill level. *Human Movement Science*, *29*(1), 103–113. http://doi.org/10.1016/j.humov.2009.05.003

Seifert, L., Leblanc, H., Herault, R., Komar, J., Button, C., & Chollet, D. (2011). Inter-individual variability in the upper-lower limb breaststroke coordination. *Human Movement Science*, *30*(3), 550–565. http://doi.org/10.1016/j.humov.2010.12.003

Takagi, H., Sugimoto, S., Nishijima, N., & Wilson, B. (2004). Differences in stroke phases, arm-leg coordination and velocity fluctuation due to event, gender and performance level in breaststroke. *Sports Biomechanics*, *3*(1), 15–27. http://doi.org/10.1080/14763140408522827

Turpin, N. A., Guével, A., Durand, S., & Hug, F. (2011). No evidence of expertise-related changes in muscle synergies during rowing. *Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology*, *21*(6), 1030–1040. http://doi.org/10.1016/j.jelekin.2011.07.013

van den Hoorn, W., Hodges, P. W., van Dieën, J. H., & Hug, F. (2015). Effect of acute noxious stimulation to the leg or back on muscle synergies during walking. *Journal of Neurophysiology*, *113*(1), 244–254. http://doi.org/10.1152/jn.00557.2014

Vilas-Boas, J. P. (1994). Maximum Propulsive Force and Maximum Propulsive Impulse in Breaststroke Swimming Technique. In A. Barabás & F. Gy (Eds.), (pp. 303–310). Presented at the ISBS - Conference Proceedings Archive, XII International Symposium on Biomechanics in Sports, Budapeste-Siófok, Hungary.

Yoshizawa, M., Tokuyama, H., Okamoto, T., & Kumamoto, M. (1976). Electromyographic study of the breaststroke. In P. V. Komi (Ed.), *Biomechanics V-B* (pp. 222–229). Baltimore, Maryland, USA.

Table 1. Between-group indices of similarity (r_{max}) and lag times (%) for individual EMG patterns and activation coefficients (mean ± SD). Note that negative lag time values indicate a backward shift in beginners compared to elites.

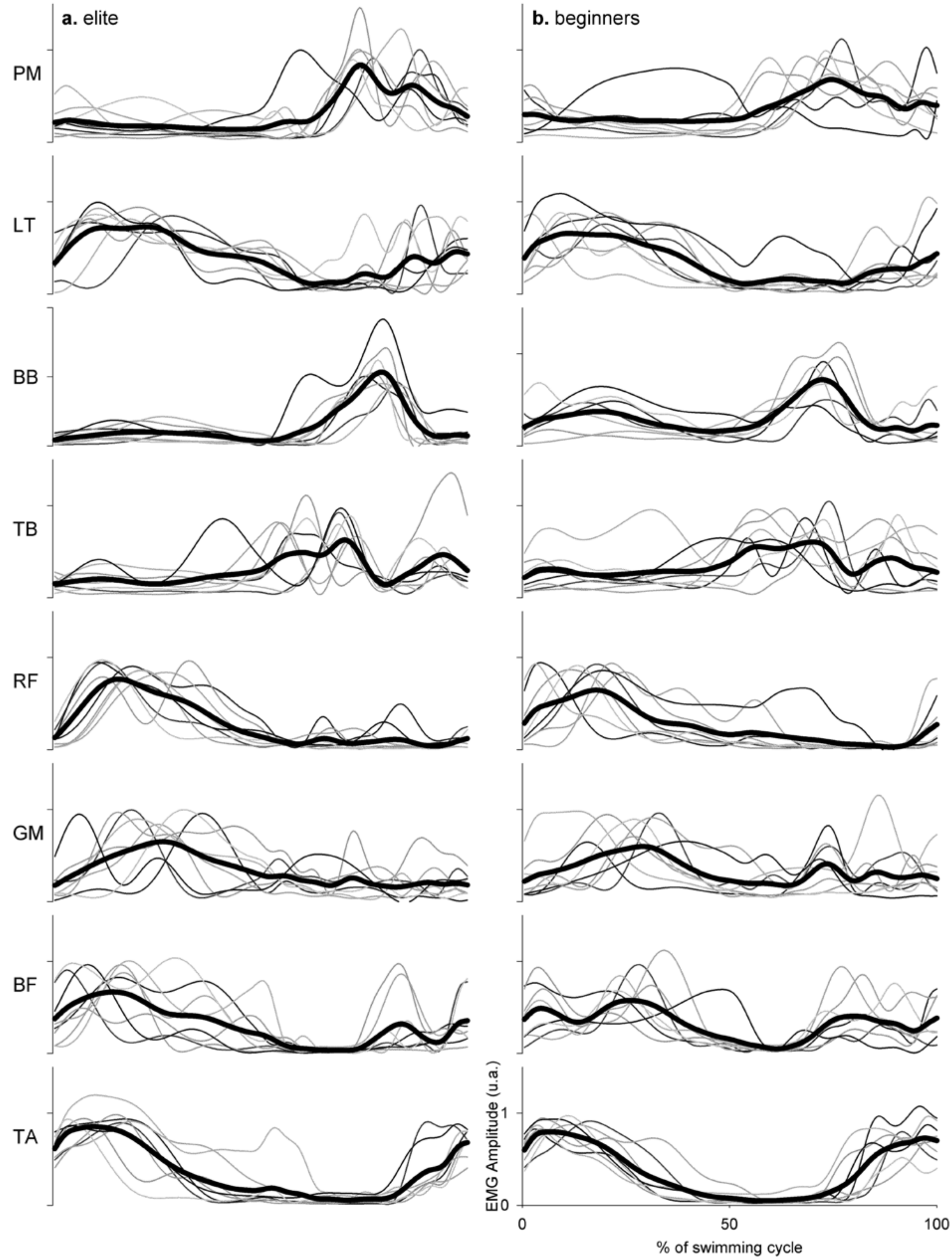
Figure 1. EMG envelope for 8 muscles obtained in each swimmer for both populations during breaststroke. The black bold line indicates the mean profile across each population, while the thin lines represent individual data.

Figure 2. Synergy activation coefficients and muscle synergy vectors across swimmers in each population. (a.) The synergy activation coefficients are shown in the left side of the figure for the two populations (i.e. elites and beginners) grouped by synergy. The black bold lines indicate the mean profile across each population, while the thin lines represent individual data. Dashed lines represent elite data. **(b.)** The muscle synergy vectors are shown at the right side of the figure aligned to the corresponding activation coefficient.

Figure 3. Muscle synergy #3 grouped by pattern similarity: synergy activation coefficients (left side) and muscle synergy vectors (right side) for all swimmers. Swimmers #1, #14 and #15 were unable to be grouped on the 3 identified patterns, particularly in terms of muscle synergy vectors (right side panel). Note that swimmers #1 to #8 are elites while #9 to #16 are beginners.

	Between-group similarity (r_{max})	Lag time %	*p-value*	*Cohen's d-value*
Individual EMG				
Pectoralis major	0.76 ± 0.17	**-6.3 ± 18.5**	**0.011**	0.34
Lower trapezius	0.69 ± 0.15	2.1 ± 15.4	0.699	0.14
Biceps brachii	0.71 ± 0.20	**-13.2 ± 21.8**	**0.000**	0.61
Triceps brachii	0.61 ± 0.15	-1.0 ± 21.0	0.944	0.08
Rectus femoris	0.84 ± 0.11	**-3.9 ± 9.7**	**0.002**	0.40
Gastrocnemius medialis	0.67 ± 0.16	3.9 ± 16.6	0.065	0.23
Biceps femoris	0.63 ± 0.15	0.2 ± 22.3	0.578	0.01
Tibialis anterior	0.79 ± 0.13	**-3.8 ± 5.8**	**0.000**	0.66
Synergy Activation Coefficients (C)				
#1	0.88 ± 0.09	-0.8 ± 9.0	0.463	0.09
#2	0.84 ± 0.12	**-8.4 ± 14.5**	**0.000**	0.58
#3	0.63 ± 0.13	3.4 ± 33.0	0.411	0.10

bold values represents significantly differences from zero;



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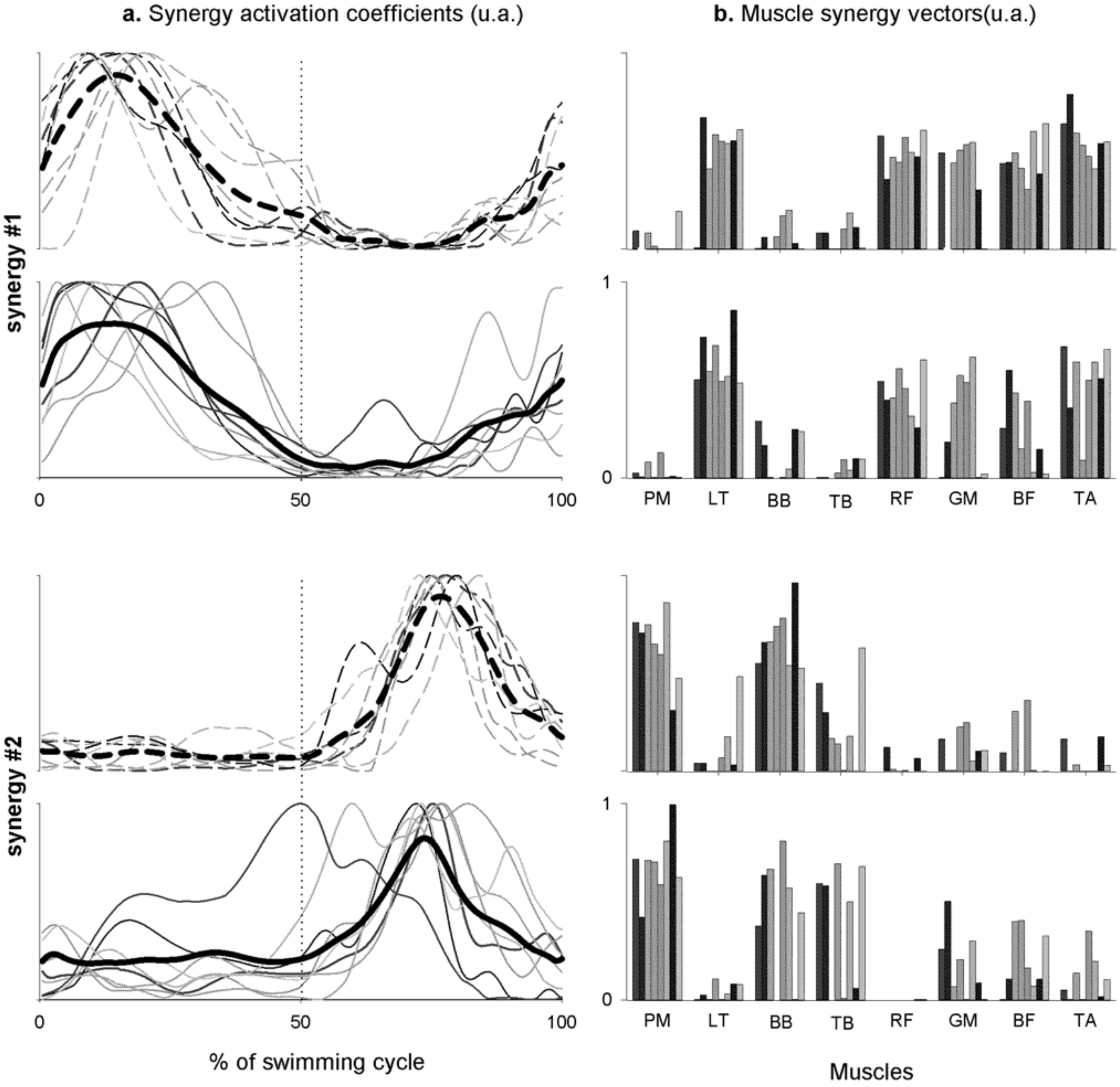

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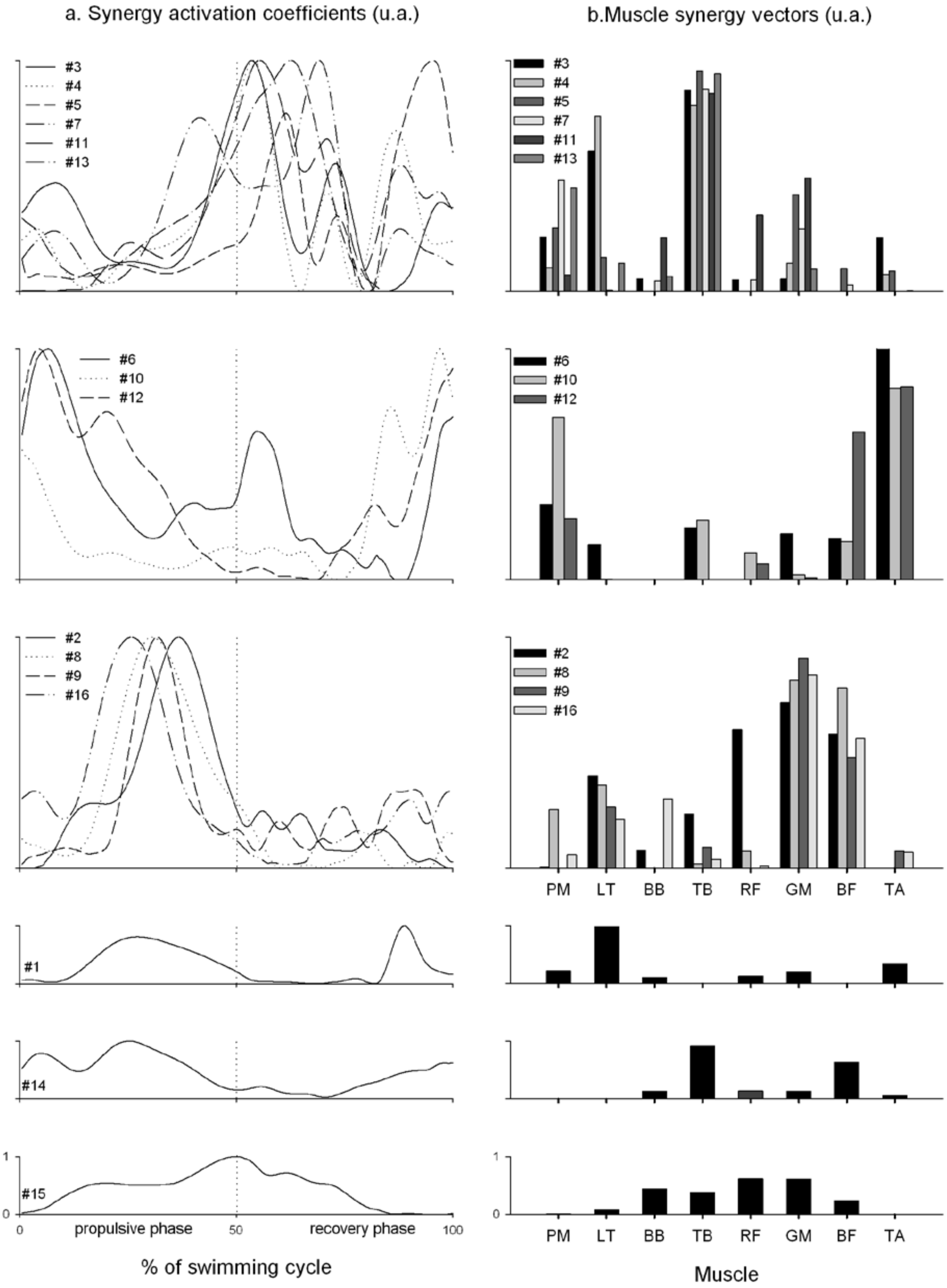

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