Muscle Activation in World-Champion, World-Class, and National Breaststroke Swimmers

Bjørn Harald Olstad, Christoph Zinner, João Rocha Vaz, Jan M.H. Cabri, and Per-Ludvik Kjendlie

Purpose: To investigate the muscle-activation patterns and coactivation with the support of kinematics in some of the world’s best breaststrokers and identify performance discriminants related to national elites at maximal effort. Methods: Surface electromyography was collected in 8 muscles from 4 world-class (including 2 world champions) and 4 national elite breaststroke swimmers during a 25-m breaststroke at maximal effort. Results: World-class spent less time during the leg recovery (P = .043), began this phase with a smaller knee angle (154.6° vs 161.8°), and had a higher median velocity of 0.18 m/s during the leg glide than national elites. Compared with national elites, world-class swimmers showed a difference in the muscle-activation patterns for all 8 muscles. In the leg-propulsion phase, there was less triceps brachii activation (1 swimmer 6% vs median 23.0% [8.8%]). In the leg-glide phase, there was activation in rectus femoris and gastrocnemius during the beginning of this phase (all world-class vs only 1 national elite) and a longer activation in pectoralis major (world champions 71% [0.5] vs 50.0 [4.3]) (propulsive phase of the arms). In the leg-recovery phase, there was more activation in biceps femoris (50.0% [15.0] vs 20.0% [14.0]) and a later and quicker activation in tibialis anterior (40.0% [7.8] vs 52.0% [6.0]). In the stroke cycle, there was no coactivation in tibialis anterior and gastrocnemius for world champions. Conclusion: These components are important performance discriminants. They can be used to improve muscle-activation patterns and kinematics through the different breaststroke phases. Furthermore, they can be used as focus points for teaching breaststroke to beginners.

Keywords: swimming, electromyography, coactivation, motion analysis, performance

Only a few athletes become world champions while others remain at the national elite (NE) level. In breaststroke swimming, as in most other activities with an endurance component, athletes reaching the highest level show the highest mean velocity throughout the competition. The velocity changes in a breaststroke cycle and kinematic variables can identify this through breaking the stroke into, for example, smaller phases and angles of the limbs. To reach the highest mean velocity several factors play an important role, including anthropometrics,1 strength,2 flexibility,3 swimming economy,4 and psychology.5 In addition, swimming technique and race tactics play an important role in the performance outcome6 together with muscle activation.7,8 Many of the factors that are required for performing at the world-class (WC) level are well documented,9,10 but only very limited knowledge is available that quantifies how muscles are coordinated and coactivated and/or the level of activation, especially in contemporary breaststroke swimming. Most of the research that has been conducted in swimming is limited to front crawl and the earlier style of breaststroke.11 Contemporary breaststroke permits the swimmer to go beneath the water surface with the head during parts of the stroke cycle, recover the arms and hands at or above the water surface, incorporate different degrees of body undulations throughout the stroke cycle, and use a deeper leg extension.12

The first study comparing the muscle-activation patterns from WC swimmers with swimmers at other performance levels13 had some methodological challenges; the absence of normalization and identification of stroke phases made it hard to compare the groups. Later, Yoshizawa et al14 found that Olympic swimmers showed longer activation of the tibialis anterior and better timing with the use of gastrocnemius. This allowed for a longer dorsiflexion of the foot, resulting in a more effective kick, than members of a university swimming club and average adults. In the best swimmer, activity of the rectus femoris was observed during the first part of gliding, showing that full extension of the knee joint occurred after the feet were almost together. That Olympic swimmer also showed higher and earlier activity in the biceps brachii (long head) during the pull phase to perform the elbow-up pull with earlier elbow flexion to achieve large propulsion. A study of lower-limb flexion-extension in the contemporary breaststroke15 found different muscle activation among international- and national-level swimmers to produce similar movements. The international-level swimmer was the only 1 to maintain muscle activity during the gliding phase to actively reach a better streamlined position to limit drag increase.

Measuring muscle activation with surface electromyography (EMG) makes it possible to observe an expression of the dynamic involvement of specific muscles in the propulsion of the body through the water.16 Such information is important for a better understanding regarding the coordination, coactivation, and intensity of activity in muscles and their relative contribution to overall propulsion. Coactivation between muscles is also generally involved in the processes of determining movement efficiency,

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safety, control of the precision, and velocity of movement and for stabilizing single joints. While coactivation is necessary during certain movements, excessive activation in antagonist muscles is associated with increased metabolic costs and an inefficient use of energy, which could lead to an earlier onset of fatigue and be detrimental to performance.

To find the optimal muscle-activation pattern it is necessary to assess it in the world’s best swimmers. It is therefore equally important to know whether there are differences between swimmers at different performance levels that can be identified as performance discriminators. Such knowledge is also important to provide coaches and swimmers with the most relevant key points for these variables. It can be used not only for improving training efficiency and technique in swimmers who wish to reach the highest level but also for teaching breaststroke to beginners, designing applicable weight training, and establishing dry-land programs. The purpose of this study was therefore to investigate the muscle-activation patterns and coactivation with the support of kinematics in some of the world’s best breaststrokers and identify performance discriminants related to national elites (NEs) at maximal effort. We hypothesized that WC swimmers would have a shorter time in the different phases and show more-effective muscle-activation patterns than NEs.

Methods

Participants

Four WC breaststroke swimmers (medalists at international championships) including 2 male world champions and 4 NEs (medalists at national championships) participated in this study (Table 1). All participants signed an informed consent before the commencement of this study. The national ethics committee approved the study protocol, and all procedures were in accordance with the Declaration of Helsinki.

Experimental Protocol

All measurements were performed on the pool deck and in a 25-m indoor swimming pool with air and water temperature of approximately 29°C. Isometric maximal voluntary contractions (MVC) were performed for each muscle. The participants were instructed to exert a maximal isometric force and hold it for 5 seconds, separated by about 45 seconds of recovery in standardized exercises. Each contraction was repeated 3 times. The joint angle during the MVCs was verified using a goniometer. After a 15-minute personalized warm-up that included low- to moderate-intensity aerobic swimming and elements of kicking and drill exercises with the testing equipment, the swimmers performed a 25-m breaststroke at maximal effort using an in-water start. Maximal effort was measured through the Borg rating of perceived exertion, and a score of 19 or 20 after completion was accepted as maximal effort.

Kinematic-Data Collection

A 3D underwater motion-capture system with automatic motion tracking (Qualisys, Gothenburg, Sweden) consisting of 6 Oqus 4 cameras with sampling frequency of 100 Hz was used for collecting kinematical variables. The cameras had no exposure delay and the flash time was 4888 μs. Calibration was performed with an L-frame reference structure and a moving wand method with 2 markers fixed with an interpont distance of 749.5 mm following the recommendations of the manufacturer. The wand was moved through the calibration volume at a slow pace to avoid wobbling of markers for a period of 300 seconds. The cameras covered a volume of approximately 37.5 m³, 10 m (x) × 2.5 m (y) × 1.5 m (z) and is presented in Figure 1. The volume was calibrated in the middle of the pool (y) starting 1 m from the end of the swim (x). Qualisys Track Manager (QTM) version 2.8 (Qualisys, Gothenburg, Sweden) was used for the camera setup and capture.

Passive spherical markers with retroreflective tape (Qualisys, Gothenburg, Sweden) developed to suit underwater use (diameter 19 mm) were embedded in silicone for fastening and had neutral buoyancy. They were attached to both sides of the swimmers’ bodies on the following reference points: crista iliaca, trochanter major, lateral femoral condyle, most posterior part of calcaneus, medial and lateral malleoli, and first and fifth metatarsals.

Surface-EMG-Data Collection

Muscle activation was recorded telemetrically with surface EMG (Plux, Lisbon, Portugal) from 8 muscles on the right side of the body: triceps brachii (lateral head), biceps brachii (long head), trapezius (pars descendens), pectoralis major (pars clavicularis), gastrocnemius medialis, tibialis anterior, biceps femoris (long head), and rectus femoris. Skin-preparation procedures, electrode configurations, and placements were performed using methods previously reported. The EMG signals were acquired according to the recommendations from the International Society of Electrophysiology and Kinesiology, with a band-pass filter of 25 to 500 Hz (–6 dB), input impedance >100 MΩ, and common-mode rejection ratio of 110 dB, amplified with a gain of 1000 and sampled at 1 kHz.

Data Processing

The pool was equipped with 4 digital underwater cameras (Sony HDR-CX550VE camcorders; Sony Corp, Tokyo, Japan). The

<table>
<thead>
<tr>
<th>n and participant type</th>
<th>Sex</th>
<th>Age (y)</th>
<th>Body mass (kg)</th>
<th>Height (cm)</th>
<th>Streamline height (cm)</th>
<th>FINA points*</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 world-class</td>
<td>Female</td>
<td>25.5 ± 4.0</td>
<td>66.2 ± 10.1</td>
<td>167.0 ± 1.4</td>
<td>213.0 ± 1.4</td>
<td>986.5 ± 10.6</td>
</tr>
<tr>
<td>2 world-class (world champions)</td>
<td>Male</td>
<td>27.3 ± 1.7</td>
<td>86.6 ± 0.8</td>
<td>188.0 ± 2.8</td>
<td>243.3 ± 1.1</td>
<td>1009.0 ± 22.6</td>
</tr>
<tr>
<td>2 national elite</td>
<td>Female</td>
<td>16.0 ± 1.9</td>
<td>63.9 ± 0.2</td>
<td>168.3 ± 6.0</td>
<td>210.5 ± 3.5</td>
<td>674.5 ± 29.0</td>
</tr>
<tr>
<td>2 national elite</td>
<td>Male</td>
<td>28.0 ± 12.1</td>
<td>83.1 ± 1.3</td>
<td>185.0 ± 2.8</td>
<td>235.8 ± 4.6</td>
<td>749.0 ± 4.2</td>
</tr>
</tbody>
</table>

* The highest number of points for each swimmer, regardless of breaststroke distance or course.
cameras were placed inside sports-pack waterproof cases (SPK-HCE; Sony Corp, Tokyo, Japan) for synchronization of the EMG and 3D recordings and to verify the swimming movements in 2D. The Sony camera captured the first blink from the EMG equipment’s reference light when EMG recording started. The EMG time log was then synchronized to the blinking onset/offset of the 3D cameras displayed in Figure 2.

QTM version 2.8 software was used to track and process the anatomical markers on the swimmers’ bodies using a fit-to-second-degree curve filter. Swim velocity, stroke length, phase time, stroke rate, and knee angle for the complete stroke cycle and for each of the phases were measured. Based on the leg kick, each stroke cycle was divided into 3 phases: leg propulsion, from the smallest knee angle during leg recovery until the first peak in knee angle (extension) during the leg propulsion; leg glide, from end of leg propulsion to the beginning of active knee flexion for leg recovery; and leg recovery, from end of leg glide until the smallest knee angle. The leg kick was chosen for phase division due to its central role in generating propulsion. In addition, it provided reliable pictures of the movement since cameras were only placed underwater and markers on the upper body left the water during certain parts of the stroke cycle.

The raw EMG signals were visually inspected to ensure their quality using MyoResearch XP Master Edition 1.08.32 (Noraxon, Scottsdale, AZ, USA), before further processing in MATLAB R2012b (MathWorks, Natick, MA, USA). The raw EMG signals were processed according to the recommendations from the International Society of Electrophysiology and Kinesiology: digitally filtered (20–500 Hz), full-wave-rectified, and smoothed with a low-pass filter (12 Hz, fourth-order Butterworth). Averaged EMG was calculated for each muscle during the stroke cycle. The EMG signals were amplitude-normalized to the individual MVC. Because different phase times were observed among the swimmers, each stroke phase was interpolated to 50 time points using MATLAB R2012b. This allowed comparison between the swimmers with respect to muscle-activation patterns within each phase.

To identify muscle-activation onset and offset, a threshold level of 20% of the peak EMG activation during the stroke cycle was selected for all muscles except gastrocnemius, which showed a higher baseline activity, and therefore the threshold level was set to 25%. Coactivation was calculated as the time of agonist–antagonist activity above the threshold level divided by the time of the stroke cycle or phase for all muscle pairs. Three to five stroke cycles within the calibrated volume were selected for further EMG and kinematic analyses.

**Statistical Analysis**

IBM SPSS Statistics version 21.0 (IBM Corp, Armonk, NY, USA) was used for all statistical computations. Mann-Whitney tests were used to test overall differences between the WC and NE swimmers’ kinematics for 16 variables. Significance was set at \( P < .05 \). Median values and the interquartile range (IQR) were used for presenting
averaged EMG and coactivation from the 50 time points during each phase.

Results

Kinematics

WCs spent less time during leg recovery \( (P = .043) \). The largest difference in mean swimming velocity was found during the leg glide, with WCs being 0.13 m/s faster than NEs. In addition, WCs started the leg recovery with a smaller knee angle than NEs (154.6° vs 161.8°). Descriptive statistics of the kinematics are presented in Tables 2 and 3.

Electromyography

The individual muscle-activation pattern remained constant throughout the 7 stroke cycles. An example for 1 NE swimmer’s triceps brachii activation is presented in Figure 3. An example of a world champion and NE swimmer regarding when the muscles were active during the stroke cycles is presented in Figure 4.

Triceps Brachii (Lateral Head) and Biceps Brachii (Long Head)

The median activation for NEs in triceps brachii during the leg-propulsion phase was 23.0% (8.8), while only 1 of the WCs showed activation beyond the threshold level (during the last 6.0%). Three of the NEs also showed activation beyond the threshold level in triceps brachii at the beginning of this phase. WCs activated biceps brachii at 53.0% (9.0) into the leg-glide phase while NEs activated at 59.0% (3.0). In addition, 1 world champion activated the biceps brachii 30% into this phase.

The triceps brachii showed most individual patterns with 2 and 3 peaks during the stroke cycle for NEs, while WCs only showed 1 (1 world champion had 2 peaks). An example of the average triceps and biceps brachii muscle coordination through the stroke cycles from 1 NE and 1 world champion is presented in Figure 5(A).

Gastrocnemius Medialis and Tibialis Anterior

All of the swimmers started the leg-propulsion phase with activation in tibialis anterior. NEs activated tibialis anterior for 87.0% (11.3) while WCs showed activation for 69.0% (12.0) of this phase. Only the 2 world champions and 1 NE showed activation in gastrocnemius at the end of this phase. The WCs showed activation in gastrocnemius at the beginning of the leg-glide phase while only 1 NE had gastrocnemius activated. The NEs started activating tibialis anterior at 52.0% (6.0) into the leg-recovery phase while WCs activated tibialis anterior for the last 40.0% (7.8). In addition, 2 NEs showed coactivation between gastrocnemius and tibialis anterior for the last 38.0% of this phase. On the contrary to all other participants, the 2 world champions showed no coactivation between gastrocnemius and tibialis anterior during the whole stroke cycle. An example of the average muscle coordination through the stroke cycles from 1 NE and 1 world champion is presented in Figure 5(B).
Table 2  Time, Length, and Velocity for the Different Phases and the Total Stroke Cycle Including Stroke Rate, Median (Interquartile Range)

<table>
<thead>
<tr>
<th>Phase/cycle</th>
<th>Time (s)</th>
<th>Length (m)</th>
<th>Velocity (m/s)</th>
<th>Stroke rate (strokes/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P</td>
<td>P</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Leg propulsion</td>
<td>.386</td>
<td>.773</td>
<td>.248</td>
<td></td>
</tr>
<tr>
<td>world-class</td>
<td>0.37 (0.09)</td>
<td>0.44 (0.23)</td>
<td>1.25 (0.35)</td>
<td></td>
</tr>
<tr>
<td>national elite</td>
<td>0.42 (0.15)</td>
<td>0.46 (0.06)</td>
<td>1.08 (0.40)</td>
<td></td>
</tr>
<tr>
<td>Leg glide</td>
<td>.559</td>
<td>.248</td>
<td>.386</td>
<td></td>
</tr>
<tr>
<td>world-class</td>
<td>0.64 (0.30)</td>
<td>0.89 (0.36)</td>
<td>1.42 (0.36)</td>
<td></td>
</tr>
<tr>
<td>national elite</td>
<td>0.60 (0.13)</td>
<td>0.81 (0.20)</td>
<td>1.24 (0.20)</td>
<td></td>
</tr>
<tr>
<td>Leg recovery</td>
<td>.043*</td>
<td>.248</td>
<td>.386</td>
<td></td>
</tr>
<tr>
<td>world-class</td>
<td>0.37 (0.09)</td>
<td>0.40 (0.13)</td>
<td>1.03 (0.35)</td>
<td></td>
</tr>
<tr>
<td>national elite</td>
<td>0.46 (0.06)</td>
<td>0.47 (0.19)</td>
<td>0.99 (0.50)</td>
<td></td>
</tr>
<tr>
<td>Total stroke cycle</td>
<td>.564</td>
<td>.386</td>
<td>.248</td>
<td></td>
</tr>
<tr>
<td>world-class</td>
<td>1.70 (0.30)</td>
<td>1.30 (0.32)</td>
<td>43.1 (9.9)</td>
<td></td>
</tr>
<tr>
<td>national elite</td>
<td>1.65 (0.35)</td>
<td>1.12 (0.31)</td>
<td>40.9 (7.8)</td>
<td></td>
</tr>
</tbody>
</table>

*Significantly different (P < .05) between world-class and national elite.

Table 3  Knee Angle (°) at the Beginning of Each Phase and the Largest Knee Angle During Leg Glide, Median (Interquartile Range)

<table>
<thead>
<tr>
<th></th>
<th>Leg propulsion</th>
<th>Leg glide</th>
<th>Leg recovery</th>
<th>Largest during leg glide</th>
</tr>
</thead>
<tbody>
<tr>
<td>World-class</td>
<td>41.7 (5.6)</td>
<td>164.9 (19.2)</td>
<td>155.5 (17.4)</td>
<td>176.3 (10.0)</td>
</tr>
<tr>
<td>National elite</td>
<td>42.4 (4.4)</td>
<td>173.2 (16.9)</td>
<td>161.9 (10.4)</td>
<td>177.0 (4.8)</td>
</tr>
<tr>
<td>P</td>
<td>.886</td>
<td>.486</td>
<td>.200</td>
<td>.886</td>
</tr>
</tbody>
</table>

Note: No significant differences (P < .05) were found between world-class and national elite.

Figure 3  — Average muscle-activation patterns from 7 complete stroke cycles for the triceps brachii (lateral head) (TB) during maximal effort for a national elite swimmer. Amplitude was normalized to the relative maximal voluntary contraction (MVC), and time was normalized to the 3 stroke phases (50 points each).
Figure 4 — An overview of the muscles activating during the different phases of the stroke cycle at maximal effort for (A) a world champion swimmer and (B) a national elite swimmer. Time was normalized to 50 points for each of the 3 stroke phases composing a complete stroke cycle. Abbreviations: TB, triceps brachii (lateral head); BB, biceps brachii (long head); TRA, trapezius (pars descendens); PM, pectoralis major (pars clavicularis); GAS, gastrocnemius (medialis); TA, tibialis anterior; BF, biceps femoris (long head); RF, rectus femoris.

Biceps Femoris (Long Head) and Rectus Femoris

Only 1 world champion started the leg-propulsion phase with coactivation, but all of the swimmers showed coactivation between biceps and rectus femoris during this phase. While all of the WCs showed activation in rectus femoris during the beginning of the leg-glide phase, only 1 NE showed activation in this muscle. WCs had biceps femoris activated for 50.0% (15.0) of the leg-recovery phase while NEs showed activation for 20.0% (14.0). An example of the average muscle coordination through the stroke cycles from 1 NE and 1 world champion is presented in Figure 5C.

Trapezius (Pars Descendens) and Pectoralis Major (Pars Clavicularis)

Of the 8 muscle groups tested, all swimmers showed the longest periods of activation for trapezius and pectoralis major relative to the stroke cycle. Six of the swimmers including both the world champions had trapezius activated throughout the leg-propulsion phase. WCs had joined activation for 34.0% (10.0) of this phase, NEs for 12.0% (12.5), while 1 of the world champions for 80%. The world champions activated pectoralis major during 71% (0.5) of the leg-glide phase, while the other swimmers activated pectoralis
major for 50.0% (4.3). An example of the average muscle coordination through the stroke cycles from 1 NE and 1 world champion is presented in Figure 5D.

Discussion
The main aim of this study was to investigate performance discriminators in muscle-activation patterns with the support of kinematical variables in WC and NE swimmers. WC swimmers showed different muscle-activation patterns and coactivation for all of the 8 muscles tested in this study compared with NEs, supporting the hypothesis of more-effective muscle-activation patterns in WC swimmers. In addition, the WC subgroup of the 2 world champions sometimes showed different results than all the other swimmers. From the kinematical hypothesis, only the leg-recovery phase showed a different result, with WC swimmers spending less time than NEs. Therefore, the kinematics will be discussed together with muscle-activation patterns as supporting parameters.
Triceps Brachii (Lateral Head) and Biceps Brachii (Long Head)

WC swimmers showed no activation in the triceps brachii during the leg-propulsion phase (except for the last 6% in 1 swimmer). Three of the NEs showed activation at the beginning of this phase. This revealed that NEs started their leg-propulsion phase before the upper body had reached the full streamlined position, as was evident in the motion capture. In addition, the activation in triceps brachii in NEs during this phase indicated that they used triceps brachii during the streamlined position of the upper body. This was in contrast to WC, who were able to rest this muscle and conserve energy during the nonpropulsive arm phase.

WCs showed an earlier activation in biceps brachii in the leg-glide phase than NEs, while 1 of the world champions activated even earlier in this phase, suggesting an even earlier elbow flexion and orientation of the propulsive surface.14

Gastrocnemius Medialis and Tibialis Anterior

All swimmers started the leg-propulsion phase with activation in tibialis anterior, demonstrating that they had dorsiflexion of the ankle at the beginning of this phase. The NEs showed a longer tibialis anterior activation than the WC swimmers, allowing a longer dorsiflexion of the foot. This was in contrast to previous findings where a longer tibialis anterior activation was found in Olympic swimmers.14 The shorter tibialis anterior activation found in WC could be explained by the evolution in breaststroke technique. Today’s style is categorized by a deeper leg extension (toward the end of the leg-glide phase) for the WC swimmers.10 By comparison, no swimmers in this study showed activation in tibialis anterior during the beginning of this phase, thereby indicating that the breaststroke technique has changed and that today’s style takes further advantage of the up-kick motion, with plantar flexion of the ankle to further reduce drag. This was also in accordance with the technique described in which the lower legs and feet recovered forward, and just before the feet reached the buttocks they were swept outward and forward,30 showing a contribution from tibialis anterior. NEs showed activation for tibialis anterior earlier in this phase than the WC, revealing an earlier transition from plantar flexion to dorsiflexion of the ankle in NEs. This was evident in the motion capture and therefore indicates that the WC activated their muscles more effectively to reduce drag during leg recovery and had a quicker transition from plantar flexion to dorsiflexion. That could also be a reason that they spent less time in this phase. In contrast to the 6 other participants, the 2 world champions showed no coactivation in gastrocnemius and tibialis anterior during the complete stroke cycle. This indicated a better movement economy between dorsiflexion and plantar flexion of the ankle to generate propulsion and reduce drag. This is in accordance with studies conducted in running17,19 where it was found that excessive coactivation was an inefficient process that increased the metabolic cost.

Biceps Femoris (Long Head) and Rectus Femoris

All of the swimmers showed coactivation in biceps and rectus femoris during the leg-propulsion phase, indicating that knee extension was generated with high power. High angular velocities for the knee during this phase in breaststroke corresponded to a powerful extension15 and could be considered a strategy for better controlling the precision and safety of the movement.

All of the WCs but only 1 NE showed activation in rectus femoris during the beginning of the leg-glide phase. This showed that full knee extension occurred after the completion of the in-sweep of the legs for WC as previously identified.14 For the WC this might point to an active strategy in performing an undulation with the hip slightly flexed and with the buttocks lifted up toward the water surface, which was evident in the motion capture. The WC swimmers spent a shorter time in the leg-recovery phase than NE swimmers, similar to published results.31 This may be because WC showed longer activation in biceps femoris during this phase than NEs. This indicated that WCs used biceps femoris more actively to bring the heels up to the buttocks for a quicker leg recovery, as previously indicated,14 to ensure minimum forward flexion of the thigh to keep water resistance to a minimum.

Trapezius (Pars Descendens) and Pectoralis Major (Pars Clavicularis)

Of the 8 muscles tested, all swimmers showed the longest periods of activation for trapezius and pectoralis major relative to the stroke cycle. Six of the swimmers, including both world champions, had trapezius activated throughout the leg-propulsion phase, therefore suggesting that trapezius was activated to maintain an upper-body streamlined position during this phase. In addition, WC had more activation in both pectoralis major and trapezius for this phase than NEs. This revealed that WC might further optimize and lengthen their upper-body streamlined position.

The hand in-sweep is often the most propulsive phase of the arm stroke.32 This can be linked to the activation in pectoralis major, which is a powerful muscle that generates forward propulsion from the upper limb. A large difference between the 2 world champions and the other swimmers was seen during the propulsive arm pull (leg-glide phase) for the pectoralis major. The 2 world champions activated their pectoralis major longer than the other swimmers during this phase. In addition, 3 of the NEs did not start activating pectoralis major until the last 25% of this phase. This implies that the world champions were able to “grab” the water earlier and generated higher forward propulsion from the arm pull while the legs guided. It also indicated that they used a more continuous coordination mode as identified when comparing the glide and continuous stroke.29

Practical Applications

The practical implications of the findings in this study may contribute to enhanced performance in today’s upcoming breaststroke.
swimmers. This suggests that coaches and swimmers could focus on the following points when evaluating breaststroke technique:

- Avoidance of excessive use of the triceps brachii during the leg-propulsion phase, which may cause an earlier onset of muscle fatigue
- Early activation in the biceps brachii during the leg-glide phase for elbow flexion to generate earlier arm propulsion
- Active use of the gastrocnemius during this phase to improve streamlined position of the feet
- Late and quick activation in the tibialis anterior during the leg-recovery phase for reducing drag
- Avoidance of excessive coactivation in the tibialis anterior and gastrocnemius during the stroke cycle, which may cause an earlier onset of muscle fatigue
- Activation in the rectus femoris at the beginning of the leg-glide phase for a full knee extension after the foot in-sweep
- Early activation in the biceps femoris during the leg-recovery phase to decrease the time spent
- Activation in the trapezius during the leg-propulsion phase to maintain upper-body streamline
- Earlier and longer pectoralis major activation during the leg-glide phase to generate higher forward propulsion from the arm pull

Such feedback about muscle activation, however, might be difficult to interpret and apply during swimming. Training exercises that focus on emphasizing the optimal recruitment pattern of agonist and antagonist muscles and the correct timing might be easier to apply. Therefore, future research should consider investigating the common techniques and drill exercises currently employed by coaches and swimmers to investigate which of these exercises develop and implement the correct muscle-activation pattern in breaststroke technique. A future focus should also be placed on dry-land exercises performed by the swimmers. For example, it is important to know which specific strength exercises on land would specifically develop and strengthen the correct muscle-recruitment pattern for breaststroke swimming at the highest level.

Limitations of the study include the fact that 3D kinematics were only measured from cameras located underwater. This meant that markers on the upper body and arms went out of the water during certain parts of the stroke cycle. Surface EMG also has limitations, and this is often related to deep-tissue muscles, adipose tissue (fat), and crosstalk. Only superficial muscles can be measured with surface EMG. More adipose tissue leads to a decrease in the amplitude of the EMG signal but was not measured in these swimmers. They were all at the elite level, and it can therefore be expected that their adipose tissue is low and our impression was that the swimmers had a homogeneous amount. Crosstalk occurs when the electrode receives signals from nearby muscles not being tested. This study tried to limit the crosstalk by ensuring appropriate electrode placements but could not avoid sliding of the skin during the swimming. A limitation can also be that the swimmers performed 1 repetition of maximal effort. This was measured through the Borg rating of perceived exertion, but a score of 19 or 20 after completion was homogeneously accepted as maximal effort. Finally, a limited sample size only allows limited conclusions to be reached.

Conclusion

In conclusion, this study revealed that distinct differences exist between WCs and NEs in terms of muscle-activation patterns, coactivation, and kinematic variables, which can help provide swimmer performance discriminators. These findings may contribute to enhanced performance in today’s breaststroke swimmers through the suggestions provided from this study regarding focus points when evaluating and training breaststroke technique.

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