Olstad, B. H., Vaz, J. R., Zinner, C., Cabri, J. M. H., Kjendlie, P.-L. (2016). Muscle coordination, activation and kinematics of world-class and elite breaststroke swimmers during submaximal and maximal efforts. *Journal of Sports Sciences, 35*, 1107-1117.

Muscle coordination, activation and kinematics of world-class and elite breaststroke swimmers during submaximal and maximal efforts

Bjørn Harald Olastad[a], João R. Vaz[b,c], Christoph Zinner[d], Jan Cabri[a] and Per-Ludvik Kjendlie[a]

[a]*Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway;*

[b]*Laboratory of Motor Behavior, CIPER, Faculty of Human Kinetics, University of Lisbon, Lisbon, Portugal;*

[c]*Escola de Turismo, Desporto e Hospitalidade, Universidade Europeia, Lisbon, Portugal and*

[d]*Department of Sport Science, Julius-Maximilians-University Würzburg, Würzburg, Germany*

Corresponding author:

Bjørn Harald Olstad[a], b.h.olstad@nih.no, Tel: (+47) 930 61 946, fax: (+47) 22 23 42 20

Co-authors:

João R. Vaz[b,c], jprvaz@gmail.com, Tel: +351 96 709 64 44
Christoph Zinner[d], christoph.zinner@uni-wuerzburg.de, Tel: +49 931 31-89432
Jan Cabri[a], jan.cabri@nih.no, Tel: +47 93443 331
Per-Ludvik Kjendlie[a], Per-Ludvik.Kjendlie@phs.no, Tel: +47 906 50 249

Word count: 3999

Affiliation where research was conducted: Norwegian School of Sport Sciences

Funding or grant awarding bodies: None

Conflict of interest: None

Disclosure Statement: The authors have nothing to disclosure.

Abstract

The aims of this study was to describe muscular activation patterns and kinematic variables during the complete stroke cycle (SC) and the different phases of breaststroke swimming at submaximal and maximal efforts. Surface electromyography (sEMG) was collected from eight muscles in nine elite swimmers; five females (age 20.3 ± 5.4 years; FINA points 815 ± 160) and four males (27.7 ± 7.1 years; FINA points 879 ± 151). Underwater cameras were used for 3D kinematic analysis with automatic motion tracking. The participants swam 25 m of breaststroke at 60%, 80% and 100% effort and each SC was divided into three phases; knee extension, knee extended and knee flexion. With increasing effort the swimmers decreased their SC distance and increased their velocity and stroke rate. A decrease during the different phases was found for: duration during knee extended and knee flexion, distance during knee extended and knee angle at the beginning of knee extension with increasing effort. Velocity increased for all phases. The mean activation pattern remained similar across the different effort levels, but the muscles showed longer activation periods relative to the SC and increased integrated sEMG (except trapezius) with increasing effort. The muscle activation patterns, muscular participation, and kinematics assessed in this study with elite breaststroke swimmers contribute to a better understanding of the stroke and what occurs at different effort levels. This could be used as a reference for optimizing breaststroke training to improve performance.

Keywords: *swimming, electromyography, motion analysis, 3D, biomechanics*

Introduction

Quantification of muscle activation during sport specific activities can provide coaches and athletes with a better understanding of the coordination and co-activation between muscles and their relative contribution to the overall propulsion in complex dynamic movements such as swimming. It is also important in order to understand movement economy at the muscular level with increasing intensity (Clarys & Cabri, 1993; Hug & Dorel, 2009). Electromyography (EMG) can be used to describe muscle participation, synchronization between muscles and muscle intensity in terms of amplitude (Clarys & Rouard, 2011) and therefore describes athletic techniques including swimming (Olstad, Zinner, Cabri, & Kjendlie, 2014).

In swimming, only a few studies investigating muscle activation with the use of EMG have been conducted. The vast majority were conducted prior to 1980 and mostly in freestyle. Clarys et al. (1988) found an increase in amplitude and number of contraction peaks of four arm muscles when swimming speed increased. In addition, Rouard, Quezel, and Billat (1992) found greater muscular recruitment at lower and higher speeds than for moderate and intermediate speeds. Only limited amount of research has been carried out in breaststroke. According to Martens, Figueiredo, and Daly (2015) the first articles that were published on muscle activation in breaststroke swimming were of low methodological quality (using the raw signal, no amplitude normalization or no phase division) and therefore impossible to determine the "normal" muscle activation pattern (Ikai, Ishii, & Miyashita, 1964; Lewillie, 1971; Tokuyama, Okamoto, & Kumamoto, 1976; Yoshizawa, Okamoto, Kumamoto, Tokuyama, & Oka, 1978; Yoshizawa, Tokuyama, & Okamoto, 1976). The first article to create a reference base for the muscle activation patterns of the upper limbs during breaststroke swimming was Ruwe, Pink, Jobe, Perry, and Scovazzo (1994).

In 1987, the Fédération Internationale de Natation (FINA) implemented a major rule change permitting head immersion in breaststroke and a new style with body undulation emerged (Van Tilborgh, Willems, and Persyn, 1988). Technique and mechanics of breaststroke swimming have thus gone through a tremendous change over the past decades from what was called the “flat breaststroke” used by every swimmer, to the modern technique of breaststroke swimming, including many different style variants.

While only a few studies have been conducted in swimming, more research has been conducted from other dynamic sports such as running and rowing regarding muscle activation and increasing effort. In running, it was found that increasing step rate (Chumanov, Wille, Michalski, & Heiderscheit, 2012) or running speed (Komi, Gollhofer, Schmidtbleicher, & Frick, 1987; Kyröläinen, Avela, & Komi, 2005) led to an increase in leg muscle activation primarily during the late swing phase indicating an anticipatory pre-activation before foot-ground contact. The coordination among the major lower-limb muscles also changed considerably from jogging to maximum sprinting were the ankle plantar flexor muscles had a dominant role in the lower speeds while hip flexor and extensor became more critical towards sprinting (Schache, Dorn, & Pandy, 2013). Similar muscle activation patterns, motor control strategies and muscle coordination were also reported during rowing. Turpin, Guével, Durand, and Hug (2011) found a significant increase in EMG activation with increased power output, but at the same time, no dramatic changes in the timing of activation or in the shape of individual EMG patterns. Guével et al. (2011) found the shape of the EMG patterns to be very similar between 65-75% and 75-85% of maximal heart rate.

On the contrary to EMG, swimming technique has frequently been analysed using kinematics conducted with motion capture (mo-cap) in 2D with interactive tracking (IT) of body markers. Recently, body parts and full body 3D underwater mo-cap of swimming movements have been described and used through IT in several studies (e.g. Figueiredo, Barbosa, Vilas-Boas, & Fernandes, 2012; Figueiredo, Kjendlie, Vilas-Boas, & Fernandes, 2012; Figueiredo, Zamparo, Sousa, Vilas-Boas, & Fernandes, 2011; Psycharakis, Naemi, Connaboy, McCabe, & Sanders, 2010; Puel et al., 2012).

When velocity in breaststroke increases, stroke distance decreases while stroke rate (SR) increases (e.g. Olstad, Zinner, Cabri, Haakonsen, & Kjendlie, 2012; Olstad, Zinner, Haakonsen, Cabri, & Kjendlie, 2012). However, at present it is not known whether these phenomena affect muscle activation and coordination in modern style breaststroke technique. The aim of this study was therefore to investigate the relationship between muscle activation in eight different muscles and kinematic stroke phases using 3D mo-cap with automatic motion tracking (AT) during three different effort levels in elite breaststroke swimmers.

Methods

Participants

Nine elite breaststroke swimmers including five females (age 20.3 ± 5.4 years; height 168.5 ± 3.7 cm; weight 64.3 ± 5.4 kg; FINA points 815 ± 160 with a range from 654-994 points) and four males (27.7 ± 7.1 years; 186.5 ± 2.9 cm; weight 84.8 ± 2.2 kg; FINA points 879 ± 151 with a range from 746-1025 points) participated in this study. There were four world-class swimmers among the participants, two females and two males, which all had won medals at international championships during the last two years. All participants agreed to participate and signed an informed consent prior to this study. The study protocol was approved by the national ethics committee, reference 2010/2893a, and were in accordance with the Declaration of Helsinki.

Experimental design

All measurements were performed on the pool-deck and in a 25 m indoor swimming pool of the university with air and water temperature of approximately 29 °C. Maximal voluntary isometric contractions (MVC) were performed for each muscle using methods previously reported (Olstad et al., 2014). After a 15 min personalised warm-up with low- to moderate-intensity aerobic swimming and elements of kicking and drill exercises, the swimmers performed 25 m breaststroke at 60%, 80% and 100% of maximal effort with 30-45 s of rest in between mimicking the 200 m, 100 m and 50 m breaststroke paces. Borg's Rate of Perceived Exertion (RPE) was used to estimate the effort level (Borg, 1998), where 11 corresponded to 60%, 15 to 80% and 19 to 100% effort (Hill, 2010).

Kinematic data collection

A 3D underwater motion-capture system (Qualisys, Gothenburg, Sweden), consisting of 6 and10 Oqus 3 and 4 cameras (100 Hz) (Figure 1), were installed in the pool to record underwater movements for kinematic analysis. All cameras had an active filtering hardware operation which reduced unwanted reflections from sunlight, bubbles and other particles and were placed inside a waterproof case (IP68/IP69K). The cameras were positioned to cover a volume of approximately 37.5 m^3, 10 m (*X*; horizontally) x 2.5 m (*Y*; width) x 1.5 m (*Z*; vertically) (Figure 1). The root mean square reconstruction error for position was 1.6 mm. Qualisys Track Manager® v2.6. (Qualisys, Gothenburg, Sweden) was used for running the camera setup and capture.

Retro reflective markers (Qualisys, Gothenburg, Sweden) developed to suit underwater usage (diameter 19 mm) were attached to the swimmers body on the following bony reference points: crista iliaca, trochanter major, lateral femoral condyle, lateral epicondyle, most posterior part of calcaneus, medial and lateral malleolus, and 1st and 5th

metatarsals. Furthermore, four marker clusters were fixed on the thigh and shank according to (Cappozzo, Cappello, Della, & Pensalfini, 1997; de Leva, 1996).

Electromyographic data collection

Muscle activation of the right triceps brachii (TB), biceps brachii (BB), trapezius (pars descendens) (TRA), pectoralis major (pars clavicularis) (PM), gastrocnemius medialis (GAS), tibialis anterior (TA), biceps femoris (BF) and rectus femoris (RF) was measured using surface EMG. These muscles were selected based on research identifying them as important for breaststroke swimming (Martens et al., 2015; McLeod, 2010; Ruwe et al., 1994; Yoshizawa et al., 1976) and because the EMG measurements of these muscles were proven reliable in the water (Olstad et al., 2014). To minimise skin impedance the electrode sites were dry shaved with disposable razors and cleaned with a 70% alcohol solution for removal of hair and dead skin. Disposable, self-adhesive, pre-gelled Ag/AgCl waterproof electrodes (triodes) with diameter of 57 mm, contact surfaces of 10 mm, inter-electrode distance of 20 mm and with snap connectors of 3.9 mm (PLUX - wireless biosignals, Lisbon, Portugal) were positioned at the midpoint of the contracted muscle belly (Clarys & Cabri, 1993) in line with the direction of the muscle fibers according to the SENIAM recommendations (Hermens et al., 1999; Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). A ground electrode was placed on the os frontalis. The electrodes were covered with insulating tape around the outside perimeter for protection against water flow during swimming. Insulating tape was also used for fixing the cables to the body to avoid movement artefacts (Rainoldi, Cescon, Bottin, Casale, & Caruso, 2004).

The EMG signals were acquired according to the recommendations from the International Society of Electrophysiology and Kinesiology (Merletti, 1999): band pass filter of 25-500 Hz (-6 dB), input impedance >100 MΩ, common mode rejection ratio of

110 dB, amplified with a gain of 1000 and sampled at 1 kHz. Before the main experiment, the quality of EMG was visually assessed in real time, both on land and underwater.

Data processing

The pool was equipped with a digital underwater camera, Sony HDR-CX550VE Camcorder, (Sony INC, Tokyo, Japan) placed inside a Sony underwater housing SPK-CXA to synchronise the EMG and 3D recordings as well as for visual inspections of the swimming movements. The Sony camera captured the first blink from the EMG equipment's reference light (marked in the EMG output file) as well as the blinking onset/offset of the 3D cameras. Qualisys Track Manager 2.6 and 2.8 were used to track and process the anatomical markers on the swimmers' body. Swim velocity, stroke distance, phase duration, SR and knee angle for the complete stroke cycle (SC) and for each of the phases were measured by following the trajectory of the different markers. Based on the leg kick, each SC was divided in three phases: (1) knee extension phase: from the smallest knee angle during recovery until the first peak in knee angle during the knee extension, (2) knee extended phase: from end of the knee extension to the beginning of active knee flexion for leg recovery, and (3) knee flexion phase: from the end of knee extended phase until the smallest knee angle.

The raw EMG signals were visually inspected to assure proper EMG activation using the MyoResearch XP Master Edition 1.08.32 (Noraxon® U.S.A. Inc., Scottsdale, AZ, USA), before further processing in Matlab R2012b (The MathWorks, Inc. Natick, MA, USA). The EMG signals were digitally filtered (20-500 Hz), full-wave rectified and smoothed with a low pass filter (12 Hz, 4^{th} order Butterworth). Averaged EMG (avgC) was calculated for each muscle during the SC and integrated EMG (iEMG) for each phase and the SC. The EMG signals were amplitude normalised to the MVC. Different SC durations were observed among the swimmers with different effort levels, so each SC was interpolated to 100 time points using Matlab. This would allow a proper comparison between the different effort levels and swimmers with respect to muscle coordination.

For identifying muscular onset and offset, a threshold level of 20% of the peak EMG activation during the SC was selected, except for GAS, which showed a higher baseline activity and therefore the threshold level was set to 25% (Hug, 2011). Electromyography reproducibility was calculated of up to 10 SC at the different effort levels and three to five SC at the stabilised swimming velocity of the last part of each swim at 60, 80 and 100% effort, respectively and were selected for further kinematic and EMG analyses.

Statistical analysis

IBM SPSS® Statistics v21.0 (IBM® Corporation, Armonk, NY, USA) and Microsoft Excel 2010 (Microsoft® software, Microsoft Corporation, Redmond, WA, USA) were used for all statistical computations. A Shapiro-Wilk analysis was used to test for normal distribution of the data. Log transformations (Ln10) were performed on the non-normally distributed data. Repeated measures analyses of variance (general linear model ANOVA) were performed to test overall differences of the EMG and kinematic variables between the SCs and the different stroke phases at 60, 80 and 100% of maximal effort. Bonferroni post-hoc corrections were carried out to test differences between effort levels.

Results

Kinematics

The SC showed a significant decrease in duration, and a significant increase in velocity and SR with increasing effort levels ($p<0.01$ – Table Ia). The relative phase duration and distance in % of the complete SC are displayed in Table Ib.

The knee extension phase started with the smallest knee angle followed by a steep increase towards the end. As effort levels increased, only velocity significantly increased whilst knee angle decreased ($p<0.05$).

During the knee extended phase, knee angle was at its largest. The knee angle stayed relatively constant during this phase, but showed some individual variations until the beginning of the knee flexion phase. A significant decrease in duration and distance was found during this phase and significant increase in velocity ($p<0.05$) with increased effort.

The knee flexion showed a rapid decrease in knee angle from the beginning until the end. This pattern was similar throughout the different effort levels. The knee flexion phase showed a significant decrease in duration and significant increase in velocity ($p<0.05$) with increased effort.

Individual breaststroke techniques were observed among the swimmers, i.e. the knee angle at the beginning of the knee extension slightly decreased with increasing effort (range: 46-38°) and different knee angle patterns (Figure 2). With increasing effort, the swimmers also slightly increased their largest knee angle during the knee extended (Figure 3). Some swimmers had knee angle between 179-180° during the knee extended phase at 100%. At 100% the SR ranged between 38-50 strokes per min from the dominant 200 m breaststrokers (lower SR) to the dominant sprinters (higher SR).

Muscle activation

Mean activation patterns remained similar across the effort levels, but all of the muscles measured demonstrated longer activation periods relative to the SC with increasing effort. The muscle activation patterns are displayed in Figure 4 and 5.

The main muscular activation was found during the phase were the muscles acted as prime movers in order to generate propulsion except for TRA. For GAS, TA, RF and BF during the knee extension phase and for TB, BB and PM during the knee extended (propulsive phase of the arms). TRA showed main activation during the knee extension.

The sum of total iEMG showed significant increase with increasing effort for the entire body (sum of all 8 muscles), $F(2, 16) = 28.06$, $p = .000$, upper body (sum of 4 muscles), $F(2, 16) = 19.08$, $p = .000$, and also for the lower body (sum of 4 muscles), $F(2, 16) = 34.17$, $p = .000$. A significant increase was found for each muscle with increased effort except for TRA. The iEMG values are presented in Table II with Post hoc analysis between 60-80%, 60-100%, and 80-100% effort.

The knee extension phase showed the highest iEMG for the four lower limb muscles and a significant increase was found for all muscles except for TRA with increased effort (Figure 4). This phase was initiated with the extension of the hip and knee with the ankle in dorsal flexion followed by a plantar flexion towards the end of this phase. This movement is initiated by a strong muscular activation of the BF followed by the RF for a powerful knee extension. TA also showed high activation during this part in the dorsal flexion of the foot (Figure 5). Towards the middle part of the knee extension, just before the ankle started going into plantar flexion, a high co-activation between GAS and TA was found.

During the knee extended TRA decreased its activation compared to the knee extension phase. At the same time, the other muscles on the upper limb started activating and contributing to generate propulsion. The arm pull started with an outward sculling motion showing some activation in TB followed by an elbow flexion for the in-sweep were PM and BB started to activate almost simultaneously contributing to high arm velocity and maximal propulsive force for the end of this phase (Figure 4). TB and BB presented greater activation in this phase with increased effort, while PM had its greatest activation during 80% and 100%. At the same time GAS, TA, BF, RF showed their lowest iEMG (Table II).

The knee flexion started with activation of BF and GAS while TA increased its activation towards the middle of this phase in bringing the ankle in dorsal flexion. RF remained quite inactive throughout the knee flexion (Figure 5). The upper limb muscles showed high activation at the beginning of this phase and finished their contribution to generate propulsion with the in-sweep of the armstroke. The TB started pre-activating again before the elbow extension during the recovery of the arms and co-activated with BB. The TRA activated through the last part of the in-sweep where the upper body was brought out of the water before the arms shooting forward and contributing to the upper body streamline position.

Discussion

This study described muscle activation patterns and muscular participation during the SC and its phases in breaststroke swimming at different effort levels in combination with kinematic variables in elite breaststroke swimmers.

Kinematics

The significant decrease for cycle distance, and the increase of velocity and SR with increasing effort are in accordance with previous studies done in competition analysis were the short distance (100 m) showed the highest velocity and SR, and the shortest cycle distance compared to the longer 200 m distance (Craig, Skehan, Pawelczyk, & Boomer, 1985; Thompson, Haljand, & MacLaren, 2000). On the other hand, when comparing elite swimmers competing in a particular distance, it is more a specific and individual combination of SR/cycle distance that will determine the velocity (Maglischo, 2003).

Since absolute duration and distance remained similar during the knee extension phase with increasing effort this might indicate that the swimmers executed a strong kick also at lower effort levels. Therefore, the increase in velocity could come from the change in knee angle giving a better mechanical advantage – i.e. the feet were pulled higher up towards the buttocks giving a longer distance to travel and to provide force on the water, as shown in Table Ia, as well as a better upper body streamline at the beginning of this phase.

The longer knee extended phase during breaststroke compared to the other competitive swimming strokes is unique. A well-known strategy which was also seen among the elite swimmers in this study was therefore to decrease the duration and distance during the knee extended phase in order to increase velocity with increasing effort.

There was a significant decrease in absolute duration and increase in velocity with increasing effort while distance remained constant during the knee flexion phase. This might indicate a more explosive recovery and a better execution in maintaining the speed and increased momentum generated from the upper body propulsion.

Muscle activation

The mean activation pattern and the coordination of the measured muscles remained similar through the different effort levels. However, the muscles showed longer periods of activation relative to the SC and increased amplitude. This was also reflected in the significant increase in iEMG for the SC with increased effort for all muscles except TRA. This is similar to the findings of Turpin et al. (2011) for the rowing cycle were significant increase in EMG activation were found with increased power output, but at the same time the timing of activation and the shape of individual EMG patterns remained similar. On the contrary Schache et al. (2013) found a change in muscle coordination from jogging (ankle plantar flexion muscles dominated) to sprinting (hip flexor and extensor muscles become more critical). This could also be reflected in the increased anticipatory pre-activation found before foot-ground contact in Komi et al. (1987) and Kyröläinen et al. (2005).

Similar to the findings of Yoshizawa et al. (1976) knee extension started with high activation of TA through the first part of the kick, indicating that the dorsiflexion of the foot was maintained for creating a good grip on the water in order to obtain large propulsive forces. During knee extension, the co-activation of BF and RF resulted in high power in the hip and knee. Additionally, the high activation of GAS towards the end indicated a shift towards ankle plantar flexion to bring the feet together with high velocity. The TRA showed its highest activation during the knee extension phase for all effort levels indicating a strong contribution in maintaining the upper body in a streamlined position as seen in the 2D video feedback. Since forward propulsion during this phase was generated from the legs, the minimal activation in TB and BB indicated an economical use of these muscles preparing them for the next phase.

As identified by Yoshizawa et al. (1976) activation was observed in RF for the first half of the knee extended phase indicating that full knee extension occurred after the completion of the leg in-sweep, see Table Ia, where the largest knee angle occurred during this phase. This might also indicate an active role of RF when the hip is slightly flexed with the buttocks lifted up towards the water surface. In addition GAS was activated during the knee extended at around 65% into the SC. The activation observed in GAS at 100% also indicates a more active role in streamlining the feet during the knee extended in order to actively decrease the drag. The longer knee extended is unique to breaststroke and might therefore explain the low activation levels of the other leg muscles. It can be considered a “resting phase” with perspective to the work of the leg muscles, but also to reduce the energy cost as seen in other marine mammals (Williams et al., 2000) and in fish (Videler & Weihs, 1982; Weihs, 1974). The highest mean velocity was found during the knee extended phase (Table Ia). The TB, BB and PM showed its peak amplitude and iEMG as they act as the prime movers for generating propulsion through this phase, while the legs were in a streamlined position for reducing the active drag and maintaining the velocity generated towards the end of the knee extension phase. The TB activated first indicating a further arm extension reaching forward and out in the water in order to generate an even longer arm pull and activation during the armstroke out-sweep. At 100% TB started activating during the knee extension phase while at 60% and 80% during the knee extended phase. In addition, BB and PM activated earlier with increasing effort. This might indicate an earlier arm stroke initiation for decreasing the time gap between continuous overlap in propulsion from the lower and upper limbs supported by Leblanc, Seifert, Baudry, and Chollet (2005) and Manley and Atha (1992). They found that the velocity increase in breaststroke with increasing effort is mainly caused by the timing of the different stroke phases where the gliding time gap between the propulsive phase of the legs and arms was reduced and not by a greater distance covered during these propulsive phases as seen in the kinematics.

The co-activation of TB and BB towards the middle of the knee extended phase was also found by Yoshizawa et al. (1976) indicating an active flexion of the forearm during the insweep of the arms as well as an elbow stabilization for energy transfer to the trunk during the most propulsive phase of the arms. In addition, they found higher and earlier activation for BB during the arm-pull in Olympic swimmers showing an earlier elbow flexion and orientation of the propulsive surface of the upper limbs. During the propulsive contribution of the arm pull our results showed that TRA went quicker and longer into rest at 100% compared to both 60% and 80% indicating an earlier start of upper body propulsion and less co-activation and a more economical use of this muscle.

During the knee flexion phase important muscular activities were found in order to bring the legs quickly back to the beginning for the next knee extension. Knee flexion was initiated through activation of BF and continued activation in GAS indicated a continued plantar flexion of the ankle to reduce drag. High activation of TA towards the end of the phase indicated a shift towards dorsiflexion of the ankle. Still, the relatively low muscle activation found in the legs during the knee flexion indicated that other muscles also contribute in this phase, for example the iliopsoas or semimembranosus and semitendinosus as observed by Onishi et al. (2002). The significant increase in activation from BB and PM during this phase with increased effort indicates a more forceful in-sweep of the arms with high hand velocities.

Limitations

In this study we chose to focus on the phases of the leg kick and connected the general arm movements to these phases. This was done because the leg kick plays a central role in generating propulsion in breaststroke. The light conditions with sunlight generating ghost markers around the water surface also hampered the accuracy of phase division for the arm stroke. Our EMG data suggests that gliding (simultaneously of both arms and legs) might not be present in our swimmers at higher effort levels. However, due to the missing phase division of the arm stroke interpretation of this finding is limited. Swimmers at this level could be expected to have a higher swimming velocity at the different effort levels than shown in this study. A reason for this might be the added drag associated with wearing the EMG equipment and the 3D markers. A study by Kjendlie and Olstad (2012) investigated the passive drag from 3D markers to be about 7-10% higher. While no study has investigated the active drag from wearing such markers, it could be expected that this also plays a significant role in terms of added resistance. In addition, this study had a limited sample size and therefore only allows limited conclusions.

Practical implications

Swimmers train with high volumes at relatively low intensities even for shorter (i.e. faster) competitive distances. Therefore, it is important to understand whether training at submaximal effort levels elicit the same muscular activation pattern as swimming at maximal effort. Our data show that the muscle activation patterns remained similar across the different effort levels indicating that most of the training sessions performed at a submaximal effort is not problematic from the point of view of muscular activation patterns. However, the muscles demonstrated longer activation periods relative to the SC with increasing effort, higher amplitude and integrated EMG. This increase in activity should be considered by coaches in terms of for example designing specific endurance, force and power training for these muscles. Also, the muscles on the upper body showed earlier activation with increasing effort (except TRA). In this way, technique exercises used for training the timing between the arms and legs should be considered during the training process.

Conclusion

Increased velocity with increasing effort came from a significant decrease in distance during the knee extended phase combined with a decrease in the duration spent for the knee extended and knee flexion phases. In addition the knee angle at the beginning of the knee extension decreased with increased effort providing a better mechanical advantage.

The muscle activation increased significantly with increasing effort except for TRA, while the muscle patterns remained fairly constant. GAS showed activation during the knee extended at 100% contributing in maintaining a better streamline position to actively reduce drag. In addition GAS had an active role in the body motion during knee extended. At higher effort the upper body muscles showed earlier activation in order to decrease the intra-cyclic velocity variations in the SC and TRA showed more economical use with less co-activation.

The muscle activation patterns remained similar across the different effort levels. This indicates that even if the major part of the swim training is performed at submaximal efforts, from the point of view of muscular activation patterns the desired training adaptions can be achieved. However, the longer muscle activation periods relative to the SC with increasing effort, higher amplitude and integrated EMG should be considered for designing specific endurance, resistance and technique exercises.

Acknowledgements

We thank all participants and their coaches for their contribution. We thank David Haakonsen for his help during testing and analysis of the data, as well as Christina Gjestvang and Anders Braastad for their time and help with preparing and measuring the participants.

Reference List

Borg, G. (1998). *Borg's Perceived Exertion and Pain Scales*. Champaign, IL: Human Kinetics.

Cappozzo, A., Cappello, A., Della, C. U., & Pensalfini, F. (1997). Surface-marker cluster design criteria for 3-D bone movement reconstruction. *IEEE Transactions on Biomedical Engineering, 44*(12), 1165-1174.

Chumanov, E. S., Wille, C. M., Michalski, M. P., & Heiderscheit, B. C. (2012). Changes in muscle activation patterns when running step rate is increased. *Gait & Posture, 36*(2), 231-235.

Clarys, J. P., & Cabri, J. (1993). Electromyogrophy and the study of sports movements: a review. *Journal of Sports Sciences, 11*(5), 379-448.

Clarys, J. P., & Rouard, A. H. (2011). The Swimming Muscle: History, Methodology and Applications of Electromyography in Swimming. In: L. Seifert, D. Chollet, & I. Mujika (Eds.). *World Book of Swimming: From Science to Performance* (pp. 43-68). Hauppauge, NY: Nova Science.

Clarys, J. P., Toussaint, H. M., Bollens, E., Vaes, W., Huijing, P. A., de Groot, G., … Cabri, J. (1988). Muscular specificity and intensity in swimming against a mechanical resistance - surface EMG in MAD and free swimming. In: B. E. Ungerechts, K. Wilke, & K. Reischle (Eds.). *Swimming science V* (pp. 191-199). Champaign, IL: Human Kinetics.

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.

de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics, 29*(9), 1223-1230.

Figueiredo, P., Barbosa, T. M., Vilas-Boas, J. P., & Fernandes, R. J. (2012). Energy cost and body centre of mass' 3D intracycle velocity variation in swimming. *European Journal of Applied Physiology, 112*(9), 3319-3326.

Figueiredo, P., Kjendlie, P. L., Vilas-Boas, J. P., & Fernandes, R. J. (2012). Intracycle velocity variation of the body centre of mass in front crawl. *International Journal of Sports Medicine, 33*(4), 285-290.

Figueiredo, P., Zamparo, P., Sousa, A., Vilas-Boas, J. P., & Fernandes, R. J. (2011). An energy balance of the 200 m front crawl race. *European Journal of Applied Physiology, 111*(5), 767-777.

Guével, A., Boyas, S., Guihard, V., Cornu, C., Hug, F., & Nordez, A. (2011). Thigh muscle activities in elite rowers during on-water rowing. *International Journal of Sports Medicine, 32*(2), 109-116.

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, 10*(5), 361-374.

Hermens, H. J., Freriks, B., Merletti, R., Hägg, G. G., Stegeman, D., Blok, J, … Disselhorst-Klug, C. (1999). *SENIAM 8: European recommendations for surface electromyography*. Enschede: Roessingh Research and Development.

Hill, J. C. (2010). Aerobic Training. In: C. C. Madden, M. Putukian, C. C. Young, & E. C. McCarty (Eds.). *Netter's Sports Medicine* (pp. 120-127). Philadelphia, PA: Saunders Elsevier.

Hug, F. (2011). Can muscle coordination be precisely studied by surface electromyography? *Journal of Electromyography and Kinesiology, 21*(1), 1-12.

Hug, F., & Dorel, S. (2009). Electromyographic analysis of pedaling: a review. *Journal of Electromyography and Kinesiology, 19*(2), 182-198.

Ikai, M., Ishii, K., & Miyashita, M. (1964). An electromyographic study of swimming. *Research Journal of Physical Education, 7*(4), 47-54.

Kjendlie, P. L., & Olstad, B. H. (2012). Automatic 3D Motion Capture of Swimming: Marker Resistance. *Medicine & Science in Sports & Exercise, 44*(5S), 476.

Komi, P. V., Gollhofer, A., Schmidtbleicher, D., & Frick, U. (1987). Interaction between man and shoe in running: considerations for a more comprehensive measurement approach. *International Journal of Sports Medicine, 8*(3), 196-202.

Kyröläinen, H., Avela, J., & Komi, P. V. (2005). Changes in muscle activity with increasing running speed. *Journal of Sports Sciences, 23*(10), 1101-1109.

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.

Lewillie, L. (1971). Graphic and electromyopgraphic analysis of various styles of swimming. In: J. Vredenbregt & J. Wartenweiler (Eds.). *Biomechanics II* (pp. 253-257). Basel: Karger.

Maglischo, E. (2003). *Swimming Fastest*. Champaign, IL: Human Kinetics.

Manley, P.K., & Atha, J. (1992). Intra-stroke velocity fluctuations in paced breaststroke swimming. In: D. MacLaren, T. Reilly, & A. Lees (Eds.). *Swimming science VI* (pp. 151-159). London: E & FN Spon.

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.

McLeod, I. (2010). *Swimming anatomy*. Champaign, IL: Human Kinetics.

Merletti, R. (1999). Standards for Reporting EMG data. *Journal of Electromyography and Kinesiology, 9*(1), III-IV.

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, 24*(5), 698-703.

Olstad, B. H., Zinner, C., Cabri, J., Haakonsen, D., & Kjendlie, P. L. (2012). Strong positive correlations were found between muscle activation and breaststroke speed measured with 3D automatic tracking. In: R. Meeusen, J. Duchateau, B. Roelands, M. Klass, B. De Geus, S. Baudry, & E. Tsolakidis (Eds.). *Book of abstracts, 17th annual Congress of the European College of Sport Science* (pp. 463-463). Bruges: European College of Sport Science.

Olstad, B. H., Zinner, C., Haakonsen, D., Cabri, J., & Kjendlie, P. L. (2012). 3D Automatic Motion Tracking in Water for Measuring Intra Cyclic Velocity Variations in Breaststroke Swimming. In: R. Meeusen, J. Duchateau, B. Roelands, M. Klass, B. De Geus, S. Baudry, & E. Tsolakidis (Eds.). *Book of abstracts, 17th annual Congress of the European College of Sport Science* (pp. 22-22). Bruges: European College of Sport Science.

Onishi, H., Yagi, R., Oyama, M., Akasaka, K., Ihashi, K., & Handa, Y. (2002). EMG-angle relationship of the hamstring muscles during maximum knee flexion. *Journal of Electromyography and Kinesiology, 12*(5), 399-406.

Psycharakis, S. G., Naemi, R., Connaboy, C., McCabe, C., & Sanders, R. H. (2010). Three-dimensional analysis of intracycle velocity fluctuations in frontcrawl swimming. *Scandinavian Journal of Medicine & Science in Sports, 20*(1), 128-135.

Puel, F., Morlier, J., Avalos, M., Mesnard, M., Cid, M., & Hellard, P. (2012). 3D kinematic and dynamic analysis of the front crawl tumble turn in elite male swimmers. *Journal of Biomechanics, 45*(3), 510-515.

Rainoldi, A., Cescon, C., Bottin, A., Casale, R., & Caruso, I. (2004). Surface EMG alterations induced by underwater recording. *Journal of Electromyography and Kinesiology, 14*(3), 325-331.

Rouard, A. H., Quezel, G., & Billat, R. P. (1992). Effects of speed on EMG and kinematic parameters in freestyle. In: D. MacLaren, T. Reilly, & A. Lees (Eds.). *Biomechanics and medicine in swimming VI* (pp. 93-97). London: E & FN Spon.

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.

Schache, A., Dorn, T., & Pandy, M. (2013). Lower-Limb Muscle Function in Human Running. In: V. Kumar, J. Schmiedeler, S. V. Sreenivasan, & H. J. Su (Eds.). *Advances in Mechanisms, Robotics and Design Education and Research* (pp. 323-327). Springer International.

Thompson, K. G., Haljand, R., & MacLaren, D. P. (2000). An analysis of selected kinematic variables in national and elite male and female 100-m and 200-m breaststroke swimmers. *Journal of Sports Sciences, 18*(6), 421-431.

Tokuyama, H., Okamoto, T., & Kumamoto, M. (1976). Electromyographic study of swimming in infants and children. In: P. V. Komi (Ed.). *Biomechanics V-B* (pp. 215-221). Baltimore, MD: University Park Press.

Turpin, N. A., Guével, A., Durand, S., & Hug, F. (2011). Effect of power output on muscle coordination during rowing. *European Journal of Applied Physiology, 111*(12), 3017-3029.

Van Tilborgh, L., Willems, E. J., & Persyn, U. (1988). Estimation of breaststroke propulsion and resistance-resultant impulses from film analyses. In: B. Ungerechts, K. Wilke, & K. Reischle (Eds.). *Swimming Science V* (pp. 67-71). Champaign, IL: Human Kinetics Publishers Inc.

Videler, J. J., & Weihs, D. (1982). Energetic advantages of burst-and-coast swimming of fish at high speeds. *The Journal of Experimental Biology, 97*, 169-178.

Weihs, D. (1974). Energetic advantages of burst swimming of fish. *Journal of Theoretical Biology*, *48*(1), 215-229.

Williams, T. M., Davis, R. W., Fuiman, L. A., Francis, J., Le Boeuf, B. J., Horning, M., … Croll, D. A. (2000). Sink or swim: strategies for cost-efficient diving by marine mammals. *Science, 288*(5463), 133-136.

Yoshizawa, M., Okamoto, T., Kumamoto, M., Tokuyama, H., & Oka, H. (1978). Electromyographic study of two styles in the breaststroke as performed by top swimmers. In: E. Asmussen & K. Jorgensen (Eds.). *Biomechanics VI-B* (pp. 126-131). Baltimore, MD: University Park Press.

Yoshizawa, M., Tokuyama, H., & Okamoto, T. (1976). Electromyographic study of the breaststroke. In: P. V. Komi (Ed.). *Biomechanics V-B* (pp. 222-229). Baltimore, MD: University Park Press.

Table Ia. Duration, distance and velocity for the different phases and the total stroke cycle. Stroke rate and knee angle at the beginning of each phase and the largest knee angle during the knee extended phase.

Kinematic variable	60% effort	95% CI	80% effort	95% CI	100% effort	95% CI	*P*-value
Duration for knee extension phase (s)	0.50 ± 0.12	(0.41) – (0.59)	0.46 ± 0.09	(0.39) – (0.53)	0.46 ± 0.07	(0.40) – (0.51)	.130
Duration for knee extended phase (s)	0.87 ± 0.24	(0.68) – (1.05)	0.70 ± 0.16	(0.58) – (0.82)	0.51 ± 0.14	(0.40) – (0.62)	.000 *abc*
Duration for knee flexion phase (s)	0.52 ± 0.09	(0.45) – (0.59)	0.45 ± 0.06	(0.40) – (0.50)	0.41 ± 0.06	(0.36) – (0.45)	.001 *abc*
Distance of knee extension phase (m)	0.47 ± 0.07	(0.41) – (0.53)	0.49 ± 0.06	(0.42) – (0.52)	0.48 ± 0.09	(0.39) – (0.57)	.850
Distance of knee extended phase (m)	1.10 ± 0.21	(0.91) – (1.30)	0.94 ± 0.22	(0.74) – (1.17)	0.82 ± 0.16	(0.66) – (0.97)	.014 *a*
Distance of knee flexion phase (m)	0.34 ± 0.07	(0.27) – (0.40)	0.36 ± 0.08	(0.27) – (0.42)	0.40 ± 0.09	(0.31) – (0.48)	.103
Total stroke cycle distance (m)	**1.90 ± 0.21**	(1.73) – (2.08)	**1.77 ± 0.22**	(1.57) – (1.95)	**1.70 ± 0.17**	(1.54) – (1.82)	.001 *ab*
Velocity in knee extension phase (m/s)	1.05 ± 0.09	(0.97) – (1.12)	1.15 ± 0.20	(0.98) – (1.32)	1.21 ± 0.20	(1.05) – (1.38)	.015
Velocity in knee extended phase (m/s)	1.20 ± 0.17	(1.07) – (1.33)	1.29 ± 0.16	(1.16) – (1.43)	1.33 ± 0.16	(1.20) – (1.46)	.010
Velocity in knee flexion phase (m/s)	0.71 ± 0.10	(0.63) – (0.79)	0.82 ± 0.15	(0.70) – (0.95)	0.97 ± 0.23	(0.78) – (1.16)	.016 *b*
Total stroke cycle velocity (m/s)	**1.04 ± 0.13**	(0.95) – (1.14)	**1.13 ± 0.15**	(1.01) – (1.24)	**1.20 ± 0.16**	(1.08) – (1.33)	.000 *abc*
Stroke rate (strokes/min)	**32.20 ± 3.43**	(29.56) – (34.84)	**38.21 ± 3.27**	(35.69) – (40.72)	**42.58 ± 4.36**	(39.23) – (45.93)	.000 *abc*
Knee angle, beginning of knee extension phase (°)	44.80 ± 2.82	(42.45) – (47.16)	43.49 ± 2.55	(41.36) – (45.62)	42.32 ± 2.56	(40.18) – (44.46)	.025
Knee angle, beginning of knee extended phase (°)	168.45 ± 7.71	(162.00) – (174.90)	168.29 ± 7.80	(161.78) – (174.81)	168.31 ± 9.32	(160.52) – (176.11)	.988
Knee angle, beginning of knee flexion phase (°)	157.23 ± 5.42	(152.70) – (161.75)	159.97 ± 7.21	(153.94) – (165.99)	158.19 ± 8.12	(151.40) – (164.98)	.521
Largest knee angle during knee extended phase (°)	175.22 ± 2.99	(172.72) – (177.72)	175.34 ± 2.68	(173.10) – (177.58)	175.73 ± 4.09	(172.32) – (179.15)	.876

Note: CI = confidence interval, *p*=overall significance between the different effort levels, *a*=significant differences between 60-80%, *b*=significant differences between 60-100%, *c*=significant differences between 80-100%.

Table Ib. Relative phase duration and distance in % of the complete stroke cycle.

Kinematic variable	60% effort	95% CI	80% effort	95% CI	100% effort	95% CI	*P*-value
Relative duration for knee extension phase (%)	23.69 ± 3.11	(21.09) – (26.29)	27.12 ± 3.91	(23.85) – (30.39)	28.24 ± 4.76	(24.26) – (32.23)	.079
Relative duration for knee extended phase (%)	50.81 ± 5.81	(45.96) – (55.67)	45.18 ± 7.62	(38.81) – (51.54)	42.39 ± 5.45	(37.83) – (46.94)	.013 *b*
Relative duration for knee flexion phase (%)	25.50 ± 3.11	(22.90) – (28.09)	27.70 ± 4.21	(24.18) – (31.22)	29.37 ± 3.14	(26.75) – (31.99)	.004 *b*
Relative distance of knee extension phase (%)	24.67 ± 3.63	(21.31) – (28.03)	26.78 ± 3.94	(23.14) – (30.43)	28.84 ± 6.60	(22.73) – (34.94)	.248
Relative distance of knee extended phase (%)	57.59 ± 6.14	(51.91) – (63.27)	53.13 ± 7.96	(45.77) – (60.49)	47.80 ± 8.15	(40.26) – (55.34)	.036
Relative distance of knee flexion phase (%)	17.74 ± 3.26	(14.73) – (20.76)	20.09 ± 5.20	(15.28) – (24.90)	23.36 ± 5.13	(18.62) – (28.11)	.009 *b*

Note: CI = confidence interval. *p*=overall significance between the different effort levels, *a*=significant differences between 60-80%, *b*=significant differences between 60-100%, *c*=significant differences between 80-100%.

Table II. Integrated EMG for the three different phases of the stroke cycle and total stroke cycle related to swimming effort.

Stroke cycle (phase)	Muscle	60% effort iEMG (mV·s)	95% CI	80% effort iEMG (mV·s)	95% CI	100% effort iEMG (mV·s)	95% CI	*P*-value
Knee extension	Triceps brachii	1.32 ± 0.70	(0.78) – (1.86)	1.84 ± .99	(1.08) – (2.61)	3.96 ± 2.67	(1.91) – (6.02)	.000 *abc*
Knee extension	Biceps brachii	1.82 ± 0.97	(1.08) – (2.57)	2.47 ± 1.35	(1.43) – (3.51)	3.06 ± 1.75	(1.71) – (4.40)	.010 *b*
Knee extension	Trapezius	7.28 ± 3.93	(4.26) – (10.30)	9.17 ± 5.09	(5.26) – (13.08)	10.18 ± 4.67	(6.58) – (13.77)	.115
Knee extension	Pectoralis	3.01 ± 3.09	(0.64) – (5.38)	4.45 ± 2.31	(2.67) – (6.23)	4.35 ± 2.63	(2.33) – (6.37)	.008 *b*
Knee extension	Gastrocnemius	5.53 ± 2.96	(3.25) – (7.80)	7.45 ± 3.76	(4.57) – (10.34)	10.51 ± 3.71	(7.66) – (13.36)	.000 *bc*
Knee extension	Tibialis anterior	10.76 ± 5.90	(6.22) – (15.30)	11.94 ± 4.52	(8.46) – (15.41)	15.22 ± 6.31	(10.37) – (20.07)	.020 *bc*
Knee extension	Biceps femoris	5.54 ± 3.16	(3.10) – (7.97)	7.65 ± 4.80	(3.97) – (11.34)	9.68 ± 4.88	(5.93) – (13.43)	.000 *abc*
Knee extension	Rectus femoris	6.87 ± 4.45	(3.46) – (10.29)	7.95 ± 4.35	(4.60) – (11.29)	10.14 ± 5.79	(5.70) – (14.59)	.000 *bc*
Knee extended	Triceps brachii	7.68 ± 4.51	(4.22) – (11.16)	9.32 ± 5.78	(4.87) – (13.76)	9.17 ± 5.85	(4.68) – (13.67)	.028 *a*
Knee extended	Biceps brachii	6.92 ± 2.28	(5.17) – (8.67)	8.57 ±.3.41	(5.96) – (11.19)	10.51 ± 5.43	(6.34) – (14.69)	.007 *b*
Knee extended	Trapezius	4.62 ± 3.07	(2.27) – (6.98)	3.93 ± 2.17	(2.26) – (5.61)	3.17 ± 1.91	(1.70) – (4.65)	.388
Knee extended	Pectoralis	7.76 ± 5.35	(3.65) – (11.87)	10.48 ± 6.97	(5.12) – (15.84)	12.14 ± 8.02	(5.97) – (18.30)	.020
Knee extended	Gastrocnemius	3.21 ± 3.21	(0.74) – (5.67)	4.72 ± 4.08	(1.59) – (7.86)	5.61 ± 4.89	(1.85) – (9.37)	.015 *a*
Knee extended	Tibialis anterior	1.09 ± 0.48	(0.72) – (1.46)	2.56 ± 1.99	(1.03) – (4.09)	2.70 ± 2.13	(1.07) – (4.34)	.011 *a*
Knee extended	Biceps femoris	0.91 ± 0.53	(0.50) – (1.32)	1.05 ± 0.43	(0.72) – (1.38)	1.32 ± 0.64	(0.84) – (1.81)	.092
Knee extended	Rectus femoris	1.49 ± 0.91	(0.79) – (2.19)	2.00 ± 1.12	(1.14) – (2.86)	2.73 ± 2.03	(1.17) – (4.29)	.007 *b*
Knee flexion	Triceps brachii	3.90 ± 2.96	(1.63) – (6.18)	4.31 ± 3.14	(1.90) – (6.73)	5.05 ± 3.42	(2.42) – (7.69)	.053
Knee flexion	Biceps brachii	6.47 ± 3.87	(3.50) – (9.45)	7.09 ± 4.41	(3.70) – (10.48)	9.32 ± 5.13	(5.37) – (13.26)	.016 *bc*
Knee flexion	Trapezius	4.35 ± 1.67	(3.07) – (5.63)	5.03 ± 2.96	(2.76) – (7.31)	4.90 ± 2.92	(2.66) – (7.14)	.965
Knee flexion	Pectoralis	8.11 ± 5.29	(4.05) – (12.17)	9.96 ± 5.49	(5.74) – (14.18)	10.25 ± 5.59	(5.95) – (14.54)	.028 *b*
Knee flexion	Gastrocnemius	2.02 ± 1.89	(0.57) – (3.47)	2.69 ± 2.44	(0.82) – (4.57)	3.29 ± 2.35	(1.48) – (5.10)	.093 *a*
Knee flexion	Tibialis anterior	5.12 ± 3.86	(2.16) – (8.09)	5.39 ± 2.51	(3.46) – (7.31)	6.84 ± 3.48	(4.16) – (9.51)	.040 *c*
Knee flexion	Biceps femoris	2.25 ± 1.28	(1.27) – (3.24)	2.65 ± 1.46	(1.52) – (3.78)	2.86 ± 1.14	(1.98) – (3.73)	.049 *a*
Knee flexion	Rectus femoris	0.77 ± 0.75	(0.19) – (1.34)	0.83 ± 0.79	(0.22) – (1.44)	1.15 ± 1.08	(0.33) – (1.98)	.017
Stroke cycle	Triceps brachii	13.13 ± 7.74	(7.18) – (19.08)	15.71 ± 9.02	(8.77) – (22.65)	18.63 ± 9.24	(11.53) – (25.73)	.000 *abc*
Stroke cycle	Biceps brachii	15.84 ± 6.03	(11.20) – (20.47)	18.78 ± 6.46	(13.81) – (23.75)	23.64 ± 8.93	(16.77) – (30.50)	.000 *abc*
Stroke cycle	Trapezius	16.55 ± 6.76	(11.35) – (21.75)	18.42 ± 8.41	(11.95) – (24.89)	18.56 ± 6.46	(13.59) – (23.52)	.622
Stroke cycle	Pectoralis	19.48 ± 10.68	(11.27) – (27.69)	25.56 ± 11.87	(16.44) – (34.68)	27.38 ± 13.95	(16.65) – (38.10)	.002 *b*
Stroke cycle	Gastrocnemius	10.95 ± 6.52	(5.94) – (15.96)	15.15 ± 8.92	(8.30) – (22.01)	19.77 ± 9.36	(12.57) – (26.96)	.000 *abc*
Stroke cycle	Tibialis anterior	17.24 ± 8.78	(10.49) – (23.99)	20.09 ± 7.60	(14.25) – (25.94)	24.99 ± 10.82	(16.67) – (33.31)	.012 *bc*
Stroke cycle	Biceps femoris	8.84 ± 3.17	(6.40) – (11.27)	11.51 ± 4.47	(8.07) – (14.95)	14.04 ± 4.54	(10.55) – (17.52)	.000 *abc*
Stroke cycle	Rectus femoris	9.26 ± 5.59	(4.97) – (13.56)	10.95 ± 5.64	(6.61) – (15.28)	14.26 ± 7.95	(8.14) – (20.37)	.000 *abc*

Note: CI = confidence interval. Integrated electromyography (iEMG) is amplitude normalised to the relative maximal voluntary contraction (MVC) and phases are time normalised to % of the stroke cycle. *a*=significant differences between 60-80%, *b*=significant differences between 60-100%, *c*=significant differences between 80-100%.

A B C D

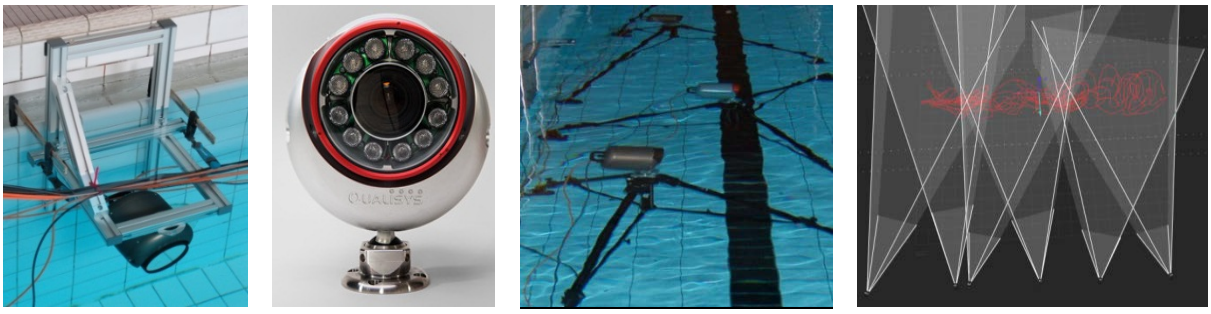

Fig. 1. Underwater cameras (A-C) and the calibrated volume under water (D).

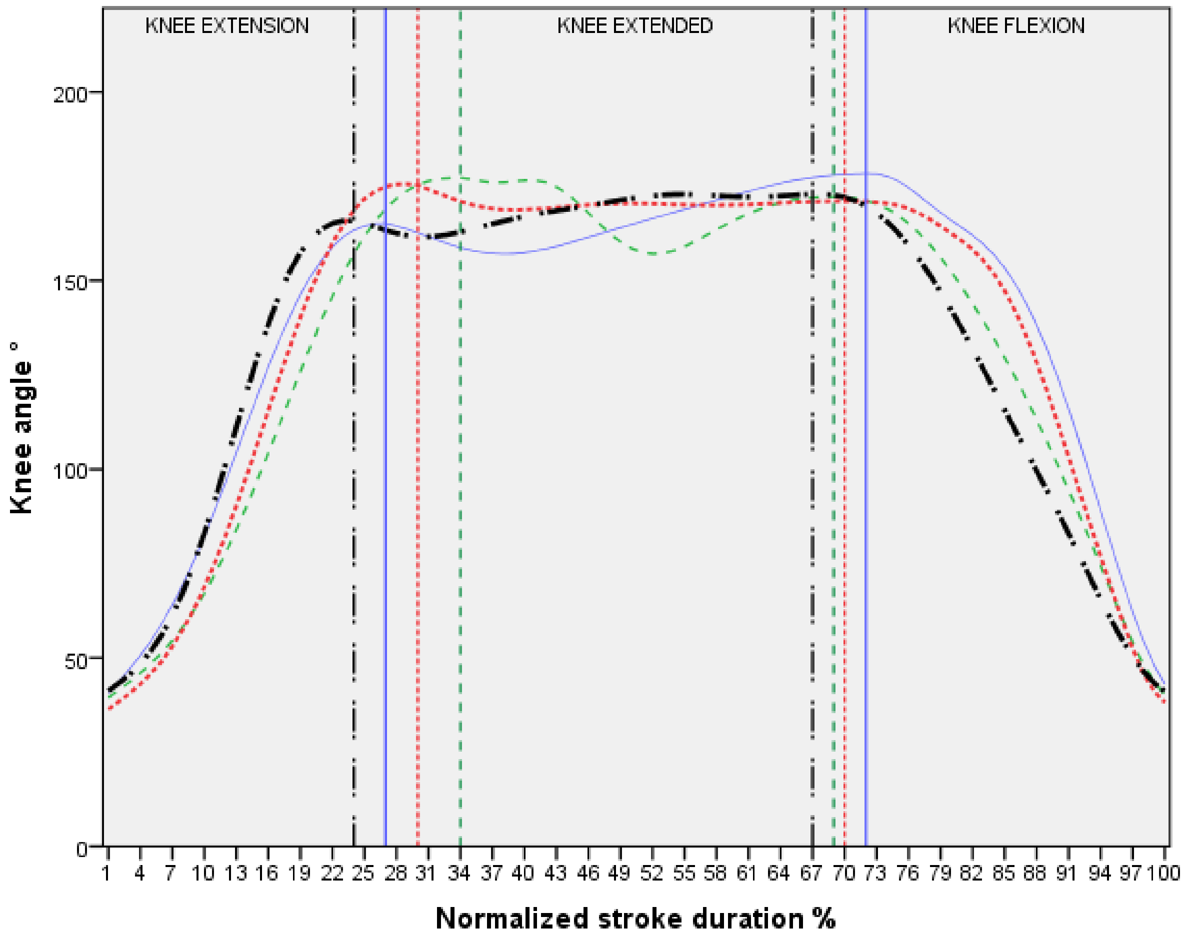

Figure 2. Individual knee angle pattern for four swimmers during the three phases of the complete stroke cycle for breaststroke swimming at maximal effort. Duration is normalised to the stroke cycle (%). —— **swimmer 1**, – – – **swimmer 2**, ····· **swimmer 3** and ·--- · **swimmer 4**.

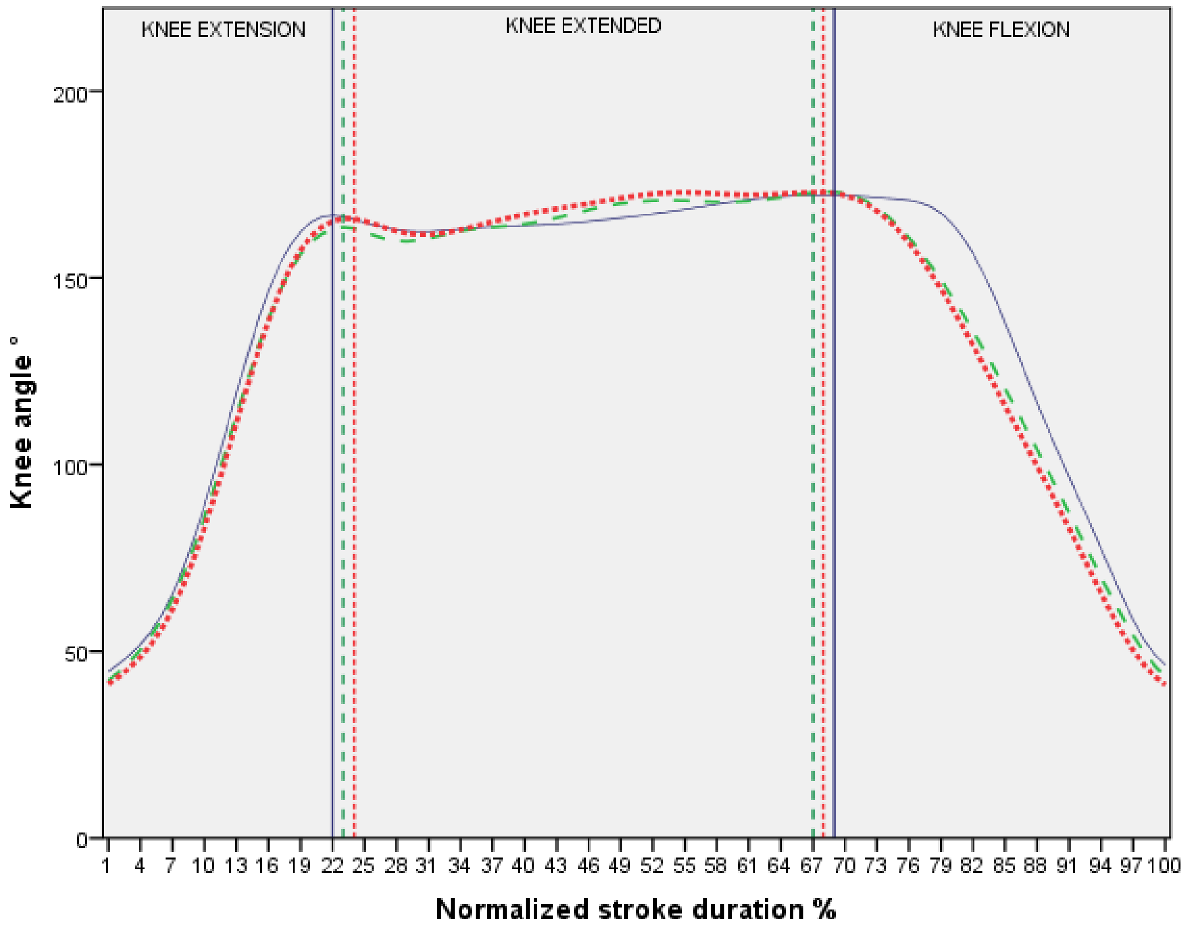

Figure 3. Knee angle pattern during breaststroke swimming at 60-80-100% of maximal effort for one swimmer during the three phases of the complete stroke cycle. Duration is normalised to the stroke cycle (%). —— **60%**, – – – **80%**, ····· **100%**.

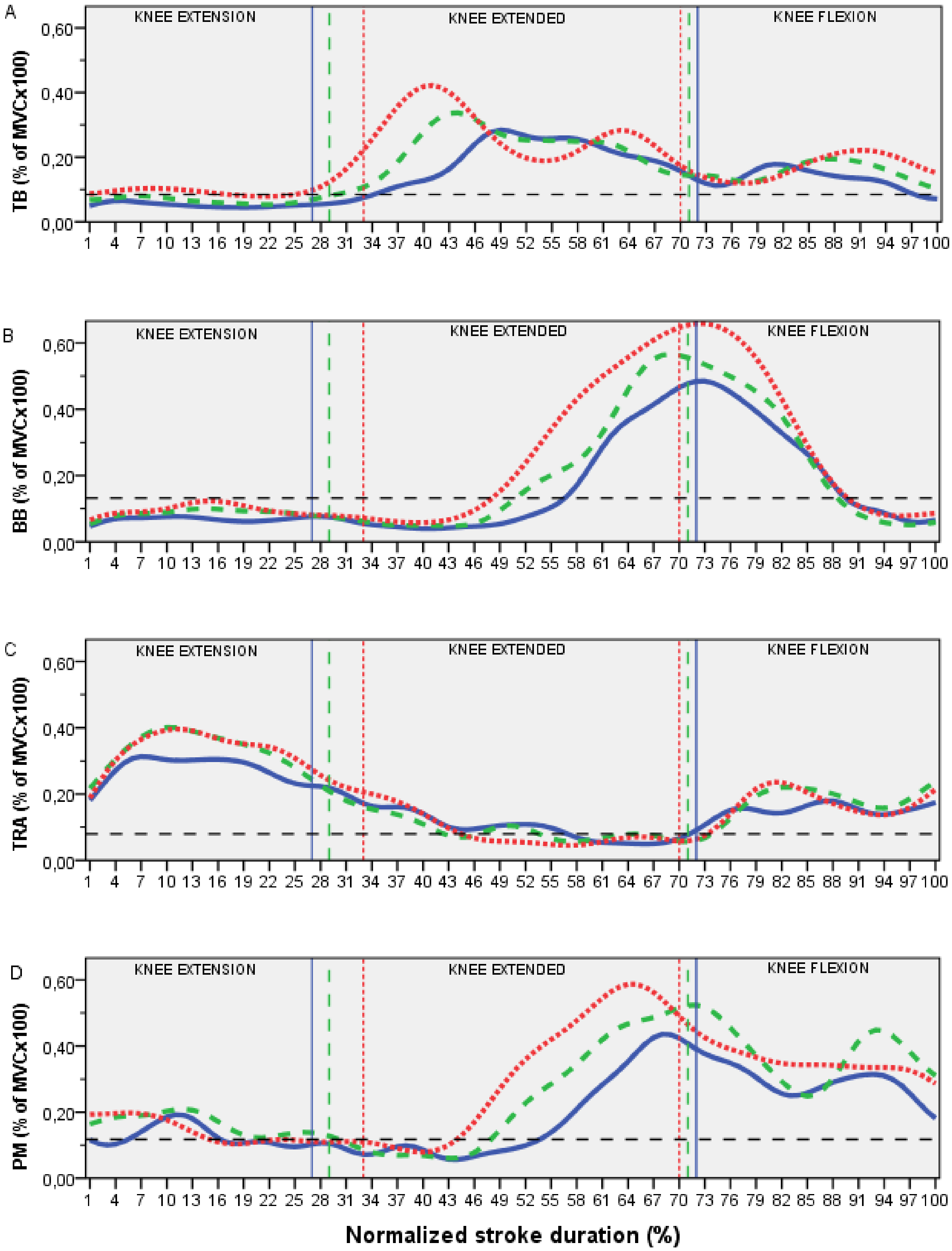

Figure 4. Average muscle activation (avgC) pattern during breaststroke swimming at 60-80-100% of maximal effort for the four muscles of the upper limb during the three phases of the complete stroke cycle. Amplitude is normalised to the relative maximal voluntary contraction (MVC) and duration is normalised to the stroke cycle (%). —— **60%**, – – – **80%**, ····· **100%**. Muscle onset and offset are determined from the avgC pattern using an EMG threshold value fixed at 20% of the peak EMG recorded during the cycle (horizontal line). Vertical lines represent the duration of the respective phases in % of the total stroke cycle. (A) TB – triceps brachii, (B) BB – biceps brachii, (C) TRA – trapezius (pars descendes), and (D) PM – pectoralis major (pars clavicularis).

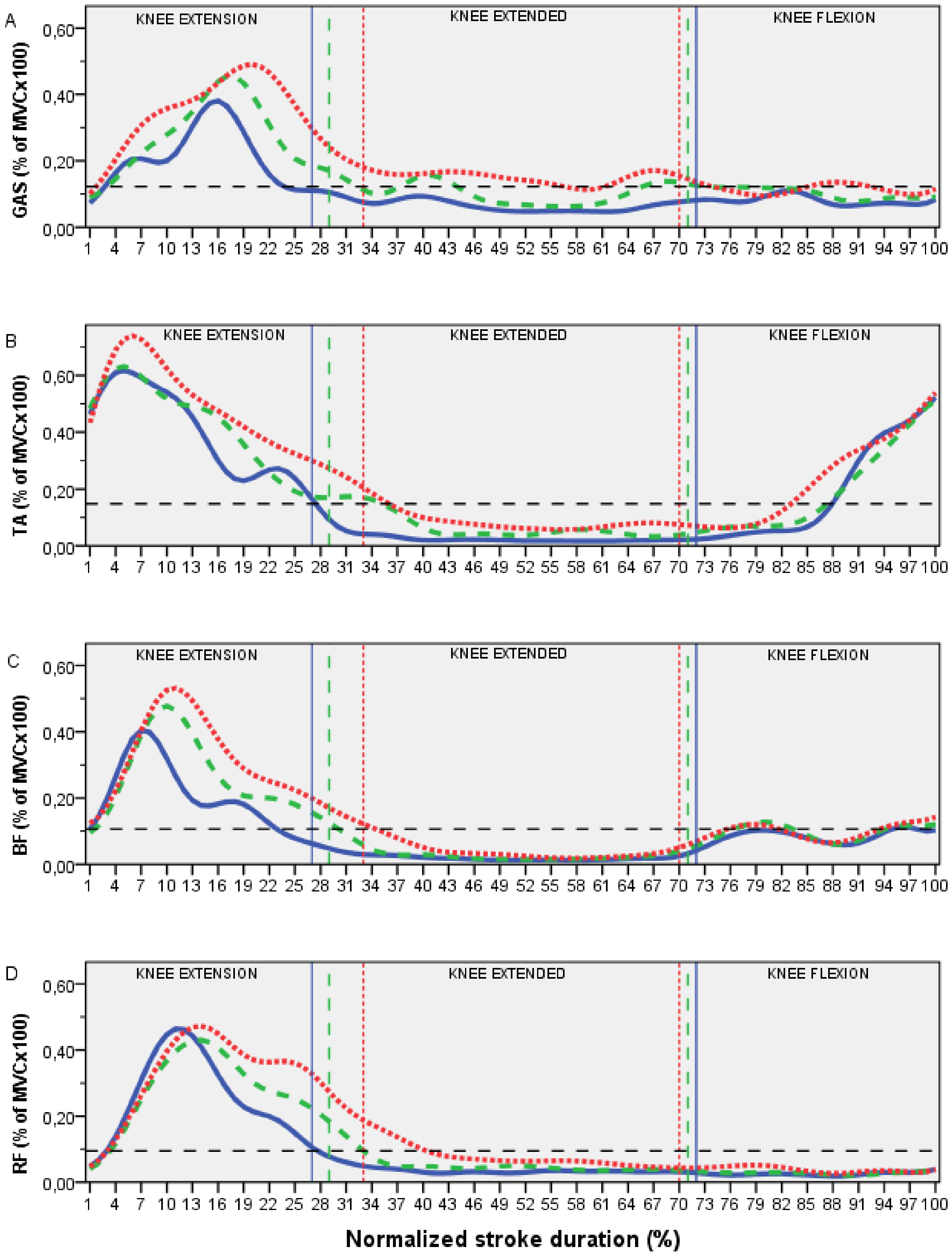

Figure 5. Average muscle activation (avgC) pattern during breaststroke swimming at 60-80-100% of maximal effort for the four muscles of the lower limb during the three phases of the complete stroke cycle. Amplitude is normalised to the relative maximal voluntary contraction (MVC) and duration is normalised to the stroke cycle (%). —— **60%**, – – – **80%**, ····· **100%**. Muscle onset and offset are determined from the avgC pattern using an EMG threshold value fixed at 20% (25% GAS) of the peak EMG recorded during the cycle (horizontal line). Vertical lines represent the duration of the respective phases in % of the total stroke cycle. (A) GAS – gastrocnemius (medialis), (B) TA – tibialis anterior, (C) BF – biceps femoris, and (D) RF – rectus femoris.