NORWEGIAN SCHOOL OF SPORT SCIENCES

Bjørn Harald Olstad

Muscle activation and kinematics in contemporary breaststroke swimming

DISSERTATION FROM THE NORWEGIAN SCHOOL OF SPORT SCIENCES · 2015

Summary

This thesis consists of five studies, the main objectives of which were to establish a reliable method for conducting surface electromyography (EMG) in water over prolonged submersion (*Study 1*); to develop a specific method for dividing the contemporary breaststroke leg kick into phases independent of the different techniques used by elite swimmers (*Study 2*); and to identify the role of neuromuscular activity in effort (*Study 3*) and performance levels (*Studies 4* and *5*) in elite contemporary breaststroke swimming.

In total, twenty-one participants (twelve students and nine elite swimmers) volunteered to participate. Muscle activation was measured with EMG from eight muscles on the right side of the body. Kinematic variables were measured from twenty-one retro-reflective markers placed on the swimmer's body. Data from these markers were captured in 3D using automatic motion tracking.

Study 1 showed that using an original electrode configuration ensuring greater surface contact with the skin, without additional waterproofing is a reliable method for acquiring EMG during prolonged submersion. The methodology allows investigation of elite and novice swimming, as well as other aquatic sports, and health and rehabilitation settings. *Study 2* divided the contemporary breaststroke leg kick into four phases, providing a specific method independent of variations in techniques used by elite swimmers: 1) propulsion, from the smallest knee angle during recovery until the first peak in knee angle during propulsion; 2) insweep/body undulation/glide from the end of phase 1 until the second peak in knee angle; 3) first part of the recovery, from the end of phase 2 until a 90 degree knee angle; and 4) second part of the recovery, from the end of phase 3 until the legs return to position 1. *Study 3* found a significant increase in integrated EMG with increasing effort (60-80-100% of maximal effort). At higher effort the upper body muscles showed earlier activation, possibly in order to decrease intra-cyclic velocity variations. Elite breaststroke swimmers used the same temporal and spatial organization of motor output at different effort levels, but demonstrated longer activation periods relative to the stroke cycle with increasing effort. *Study 4* found that the inter-stroke variability in EMG and kinematical parameters is low in elite swimmers. Distinct differences between world champions (WC+), world-class (WC) and national elite (NE) breaststroke swimmers were found in *Studies 4* and *5;* WC swimmers showed a higher gastrocnemius activity towards the end of the leg kick, a higher rectus femoris activity at the beginning of gliding, an earlier activation in biceps femoris during leg recovery, a shorter coactivation and a more economical use of the muscles compared to NE swimmers.

This thesis provides descriptions of contemporary breaststroke from a neuromuscular perspective in elite swimmers. This knowledge can be used for improving training efficiency and technique in competitive swimmers, but also for teaching beginners and designing applicable weight training and dry-land programs.

Sammendrag

Denne doktorgraden består av fem studier hvor hovedmålene var å etablere en pålitelig metode for å måle overflate elektromyografi (EMG) under vann, over en lengre periode (*Studie 1*); å utvikle en spesifikk metode for å dele det moderne brystbensparket inn i faser, uavhengig av forskjellige teknikker som brukes av elitesvømmere (*Studie 2*); å identifisere rollen til nevromuskulær aktivitet i forhold til innsats (intensitet) (*Studie 3*) og prestasjonsnivå (*Studiene 4* og *5*) hos elitesvømmere i moderne brystsvømming.

Totalt tjueen personer (tolv studenter og ni elite svømmere) meldte seg frivillig til å delta. Muskelaktivering ble målt med EMG fra åtte forskjellige muskler på høyre side av kroppen. Kinematiske variabler ble målt fra tjueen retro-reflekterende markører plassert på svømmerens kropp. Data fra disse markørene ble filmet i 3D ved hjelp av automatisk bevegelsessporing.

Studie 1 viste at å bruke en original elektrodekonfigurasjon som sikrer større kontaktflate mot huden, uten ekstra impregnering, er en pålitelig metode for å måle EMG under langvarig opphold i vann. Metoden kan brukes til å gjennomføre eksperimenter med både elitesvømmere og nybegynnere i svømming, så vel som i andre vannbaserte idretter, og innenfor helse og rehabilitering. *Studie 2* delte det moderne brystbensparket inn i fire faser som gir en bestemt metode uavhengig av variasjoner i teknikker som brukes av elitesvømmere: 1) fremdrift, fra den minste knevinkelen under opptrekket til den første toppen i knevinkelen under fremdriftsfasen; 2) avslutning av bensparket/bølgebevegelse/ gli, fra slutten på fase 1 til den andre toppen i knevinkelen; 3) første delen av opptrekket, fra slutten av fase 2 til en 90 graders knevinkel; og 4) andre del av opptrekket, fra slutten på fase 3 til bena er tilbake i posisjon 1. *Studie 3* fant en signifikant økning i integrert EMG med økende innsats (60-80-100% av maksimal innsats). Ved høyere innsats viste musklene i overkroppen en tidligere aktivering, muligens for å redusere hastighetsvariasjoner i syklusen. Elite brystsvømmere brukte den samme motoriske organiseringen med tanke på tid og rom under ulike innsatsnivåer, men demonstrerte lengre aktiveringsperioder i forhold til syklusen med økende innsats. *Studie 4* fant lav variasjon i EMG og kinematiske variabler hos elitesvømmere mellom sykluser. Tydelige forskjeller ble funnet mellom brystsvømmere, verdensmestere (WC+), verdensklasse (WC) og nasjonal elite (NE), i *Studiene 4* og *5.* WC svømmere viste en høyere aktivitet i gastrocnemius mot slutten av bensparket, en høyere aktivitet i rectus femoris i begynnelsen av glifasen, en tidligere aktivering i biceps femoris under opptrekket av bensparket, mindre koaktivering og en mer økonomisk bruk av musklene i forhold til NE svømmere.

Denne avhandlingen gir beskrivelser av moderne brystsvømming fra et nevromuskulært perspektiv hos elitesvømmere. Denne kunnskapen kan brukes til å bedre treningseffekten og teknikken hos konkurransesvømmere, men også til å undervise nybegynnere, utforme styrke- og landtreningsprogrammer.

Acknowledgments

This Ph.D. thesis was undertaken in the Department of Physical Performance at the Norwegian School of Sport Sciences, Oslo, Norway.

I would especially like to thank my supervisors and mentors Dr. Per-Ludvik Kjendlie and Prof. Dr. Jan Cabri who gave me the opportunity, means, time and support to complete this thesis in a multinational collaboration. Thank you for taking me under your wings, providing many great discussions, thoughts, time and hope throughout this journey and sticking with me to the end. It was truly great to have your guidance, constructive feedback, friendship and backing whenever it was needed.

A big thank you goes to Christoph Zinner who has been a very important collaborator during the planning and conduction of the *Studies.* Thank you for all your help, discussions and for your friendship.

Further, I would like to thank the people who have contributed to different parts of the *Studies* in addition to those mentioned above: Brice Guignard, João Rocha Vaz, David Haakonsen, Jessy Lauer, David Simbanña Escobar, Christina Gjestvang, Anders Braastad and Annie Hélène Rouard.

My thanks and gratefulness goes further to all of the elite swimmers, their coaches, national team coach Petter Løvberg and the students who have participated in different aspects of the thesis studies. Thank you for all the hard work and for taking the time to participate in my experiments.

I would also like to thank my colleagues at the Department of Physical Performance and especially my co-workers within swimming; May Grydeland, Marcel Mendritzki, Rodrigo Alvez, Bob Stallmann and everyone who has worked at NIH Svømmeskole for many great teaching sessions and discussions about swimming and my Ph.D. work.

My final thanks goes to my family and friends: my parents Brit and Terje for always supporting me and having the faith that I would complete this journey; my brother Øivind and his two wonderful kids Amalie and Magnus, who let me play with them whenever I have some free time; and a very special and warm thank you goes to my wife Daniela, for your patience, support, guidance, cooperation and for all your constructive help and feedback throughout these years and in life in general. You were worth the wait and soon we can go and enjoy our honeymoon.

In memory of Alexander Dale Oen.

Oslo, September 2015

Bjørn Harald Olstad

Abbreviations

%	Percent
°	Degrees
x	Multiplied
<	Smaller than
>	Greater than
*	$p < 0.05$
**	$p < 0.01$
2D	Two-dimensional space
3D	Three-dimensional space
avgC	Averaged electromyogram
ARV	Average rectified value
BB	Biceps brachii
BF	Biceps femoris
CI	Coactivation index
CM	Center of mass
cm	Centimeter
CNS	Central nervous system
EMG	Electromyography (from p. 2, surface electromyography)
FFT	Fast Fourier Transform
FINA	Fédération Internationale de Natation
FOV	Field-of-view
GAS	Gastrocnemius medialis
Hz	Hertz
ICC	Intraclass correlation coefficient
iEMG	Integrated electromyogram
iMVC	Isometric maximal voluntary contraction
IS	Intra stroke
ISEK	International Society for Electrophysiology and Kinesiology
IVV	Intra-cyclic velocity variations
kg	Kilograms
m	Meter
MAV	Mean absolute value
min	Minute

ms	Milliseconds
MVC	Maximal voluntary contraction
n	Sample number (participant number)
NE	National elite
NSD	Norwegian Social Science Data Services
PM	Pectoralis major (pars clavicularis)
PSD	Power Spectral Density
PV	Peak value
REK	Regional Committees for Medical and Health Research Ethics of Southern Norway
RF	Rectus femoris
RMS	Root-mean-square
RPE	Rate of Perceived Exertion
s	Seconds
SC	Stroke cycle
SD	Standard deviation
SI	Stroke index
SL	Stroke length
SR	Stroke rate (strokes$\cdot$min^{-1})
TA	Tibialis anterior
TB	Triceps brachii
TP	Two consecutive EMG peaks
TRA	Trapezius (pars descendens)
VL	Vastus lateralis
VM	Vastus medialis
W	Watts
WC	World-class
WC+	World champion(s)
yrs	Years

List of Papers

This thesis is based on the following studies, but unpublished results related to the studies will also be presented. The studies are referred to in the text with their headings. The published studies are reprinted with the permission from the publisher.

Study 1

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.

Study 2

Olstad, B.H., Zinner, C., Haakonsen, D., Cabri, J., & Kjendlie, P.L. (2014). A new approach for identifying phases of the breaststroke wave kick and calculation of feet slip using 3D automatic motion tracking. In B. Mason (Ed.), *Proceedings of the XIIth International Symposium on Biomechanics and Medicine in Swimming* (pp. 195-199). Canberra, Australia: Australian Institute of Sport.

Study 3

Olstad, B.H., Vaz, J.R., Zinner, C., Cabri, J., & Kjendlie, P.L. Muscle coordination and kinematics in world-class and national-elite breaststrokers at 60-80-100% of maximal effort. Submitted (2nd review) to *Journal of Sports Sciences.*

Study 4

Guignard, B., **Olstad, B.H**., Escobar, D.S., Lauer, J., Kjendlie, P.L., & Rouard, A.H. (2015). Different muscular recruitment strategies among elite breaststrokers. *International Journal of Sports Physiology and Performance*. Advance online publication, doi: 10.1123/ijspp.2014-0498.

Study 5

Olstad, B.H., Zinner, C., Vaz, J.R., Cabri, J., & Kjendlie, P.L. Muscle coordination differences in world champions, world-class and national elite breaststroke swimmers. Submitted to *Scandinavian Journal of Medicine and Science in Sports*.

List of additional outcomes not included in the Ph.D. thesis

Published in Journals

Pimentel, A., Gomes, R., **Olstad, B.H.**, & Gamboa, H. (2015). A New Tool for the Automatic Detection of Muscular Voluntary Contractions in the Analysis of Electromyographic Signals. *Interacting with Computers*, *27*(5), 492-499.

Lauer, J., **Olstad, B.H.**, Minetti, A., Kjendlie, P.L., & Rouard, A.H. (2015). Breaststroke swimmers moderate internal work increases toward the highest stroke frequencies. *Journal of Biomechanics,* Advance online publication, doi: 10.1123/ijspp.2014-0498.

Kjendlie, P.L., & **Olstad, B.H.** (2012). Automatic 3D motion capture of swimming: marker resistance. *Medicine & Science in Sports & Exercise* 44(5), S320.

Olstad, B.H., Cabri, J., Zinner, C., Nunes, N., & Kjendlie, P.L. (2011). SEMG measurements on land and in water prior to and after 60-90 minutes of submersion (swimming) are highly reliable. *Portuguese Journal of Sport Sciences* 11 (Suppl. 2), 763-765.

Published papers in proceedings or other, with peer review

Guignard, B., **Olstad, B.H.**, Escobar, D.S., Lauer, J., P.L., & Rouard, A.H. (2015). Knee and ankle muscles coactivations in breaststroke swimming kick and recovery: Exploratory approach. *33rd International Conference on Biomechanics in Sports*. Poitiers, France: International Society of Biomechanics in Sports. http://isbs2015.sciencesconf.org/57300/document.

Olstad, B.H., Lauer, J., Zinner, C., Haakonsen, D., Cabri, J., & Kjendlie, P.L. (2014). Muscle activation and kinematic differences between breaststroke swimming and technique/drill exercises: a case study of a world champion breaststroker. In B. Mason (Ed.), *Proceedings of the XIIth International Symposium on Biomechanics and Medicine in Swimming* (pp. 200-205). Canberra, Australia: Australian Institute of Sport.

Abstracts with oral presentation

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 of the 17th Annual Congress of the European College of Sport Science* (p. 22). Bruges, Belgium: European College of Sport Science.

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 of the 17th Annual Congress of the European College of Sport Science* (p. 463). Bruges, Belgium: European College of Sport Science.

Olstad, B.H., Cabri, J., Zinner, C., Nunes, N., & Kjendlie, P.L. (2011). Mean and Peak Frequency in the Semg Power-Spectrum is Not Different Between Land and Water. In N. T. Cable, & K. George (eds.). *Book of Abstracts of the 16th Annual Congress of the European College of Sport Science* (p. 301). Liverpool, United Kingdom: European College of Sport Science.

Abstracts with poster presentation

Olstad, B.H., Grydeland, M., Vaz, J.R., Zinner, C., Cabri, J., & Kjendlie, P.L. (2015). Muscle Activation of World-Class Breaststroke Swimmers. In A. Radmann, S. Hedenborg, & E. Tsolakidis (eds.). *Book of Abstracts of the 20th Annual Congress of the European College of Sport Science* (p. 469). Malmö, Sweden: European College of Sport Science.

Grydeland, M., **Olstad, B.H.**, Cabri, J., & Kjendlie, P.L. (2015). Muscle Activation and Kinematic Differences Between Female and Male Elite Breaststroke Swimmers. In A. Radmann, S. Hedenborg, & E. Tsolakidis (eds.). *Book of Abstracts of the 20th Annual Congress of the European College of Sport Science* (pp. 469-470). Malmö, Sweden: European College of Sport Science.

Kjendlie, P.L., Haakonsen, D., & **Olstad, B.H.** (2014). Automatic 3D underwater motion capture is highly accurate. In: *Program & Book of Abstracts, XIIth International Symposium for Biomechanics and Medicine in Swimming* (p. 164). Canberra, AUS: Australian Institute of Sport.

Guignard, B., Simbana, E.D., **Olstad, B.H.**, Kjendlie, P.L., Lauer, J., & Rouard, A.H. (2013). Ecological kinematics and electromyography approach of the lower limb in breaststroke. *15th International Congress of the ACAPS*. Grenoble, France.

Table of contents

1. Introduction

1.1 Rationale for the thesis

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. Force is applied to the water in order to overcome drag and to generate forward propulsion. In all of the strokes used in competitive swimming the mean swimming velocity of one stroke cycle (SC) is the product of the stroke rate (SR) and the distance per stroke (Craig & Pendergast, 1979). In order to reach the highest mean velocity throughout a competition several factors play an important role, including anthropometrics (Keskinen, Tilli, & Komi, 1989; Kjendlie & Stallman, 2011; Toussaint, de Looze, van Rossem, Leijdekkers, & Dignum, 1990; Toussaint, Janssen, & Kluft, 1991), strength (Colman, Daly, Desmet, & Persyn, 1992; Geladas, Nassis, & Pavlicevic, 2005; Kjendlie & Stallman, 2011), flexibility (Colman et al., 1992; Persyn, Colman, & Ungerechts, 2000), swimming economy (Capelli, 1999; di Prampero, Pendergast, & Zamparo, 2011; Minetti, 2004) and psychology (Abbott & Collins, 2004; Mahoney, Gabriel, & Perkins, 1987). In addition, swimming technique and race tactics play an important role in the performance outcome (Holmér, 1992; Mason & Formosa, 2011; Toussaint & Truijens, 2005). Many of the factors that are required for performing at the world-class (WC) level are well documented (e.g. Davison, Van Someren, & Jones, 2009; Savage & Pyne, 2011; Smith, Norris, & Hogg, 2002). Muscle activation is also linked to performance (Castronovo, Conforto, Schmid, Bibbo, & D'Alessio, 2013; Figueiredo, Pendergast, Vilas-Boas, & Fernandes, 2013; Holmér, 1992), but most of the research that has been conducted in swimming is limited to front crawl (Martens, Figueiredo, & Daly, 2015). Only very limited knowledge is available about the way muscles are coordinated and coactivated, or about the level of activation, especially in contemporary breaststroke swimming.

To measure muscle activation during sports and different forms of exercise, the established and accepted method is electromyography (EMG) which records action potentials (electrical activity) in the skeletal musculature (Clarys & Cabri, 1993). In the past, the reliability of EMG measurements has mainly been investigated for dry land sports. Therefore, before applying EMG in the aquatic environment, it is important to make sure that surface EMG (hereafter EMG) measurements obtained in water are reliable. The use of EMG in water is different from dry land conditions. The aquatic environment presents potential research challenges due to possible water leakage into the equipment and difficulties in gluing electrodes to the body for prolonged periods of time. Previous studies have reported conflicting results in terms of the reliability of EMG in water and only a few muscles have previously been investigated (Table 2, p. 28) and are further described in chapter 2.4.6, p, 28. Since many muscles influence performance in swimming, it is important to investigate additional muscles from different limbs involved in aquatic movements. Further, no previous studies have looked at reliability over prolonged submersion. Since prolonged submersion is necessary for conducting swimming experiments it is vital to establish a reliable method for measuring EMG in water over prolonged periods of time, not only for measuring elite and novice swimmers, but also for conducting experiments in other aquatic sports, and for developing exercises for rehabilitation of injuries and chronic diseases.

Before using EMG to analyze swimming movements it is important to consider an appropriate stroke phase division. Full SC kinematics have some limitations in terms of developing strategies for improving performance in complex techniques such as breaststroke swimming. Therefore, a further breakdown of the stroke into smaller phases is needed in order to better understand what occurs during the SC with different techniques and coordination modes to identify potential performance discriminators. Some previous analysis models assume that the breaststroke kick finishes with the feet actively coming together during the insweep, followed by a streamlined glide and active knee bend to start the recovery and further described in chapter 2.3.3, p. 12. However, in contemporary breaststroke, these phases cannot always be accurately separated due to the different body undulations in the technique influencing the insweep and knee bend timing during leg recovery. Therefore, a specific method for breaking the contemporary breaststroke leg kick into phases that encompass all the different styles used by elite swimmers is needed.

After establishing a specific method for dividing the SC into phases, EMG recordings make it possible to observe an expression of the dynamic involvement of specific muscles in the propulsion of the body through the water (Clarys, 1985). Such recordings provide a description of swimming technique in terms of muscle participation, synchronization and intensity (Clarys & Rouard, 2010). 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. With an understanding of muscle activation patterns, coaches and athletes can focus on a particular phase in the motion, train a particular muscle group, and better plan the use of specific equipment or training interventions (Clarys & Cabri, 1993; Hug & Dorel, 2009).

Only a few studies have investigated muscle activation with the use of EMG in breaststroke swimming (Table 3, p. 30). Most of them were conducted prior to the Fédération Internationale de Natation (FINA) rule change in 1987, which led to substantial changes in the breaststroke technique. Therefore, an investigation of the contemporary breaststroke technique is needed to understand muscle activation and coordination during the stroke and to further develop strategies for swimming more efficiently. Also, within today's top-level sports, small margins are crucial and very difficult for the human eye to detect. Studying how muscles are activated and coordinated will further provide "a look inside" the body to detect performance discriminators.

Even though the way muscles are activated and coordinated during maximal swimming is of great interest, swim training is for the most part performed at submaximal effort levels. Therefore, it is important to know whether swimming at submaximal effort levels trains the same muscle activation pattern that is used while competing at maximal effort. It is also important in order to understand movement economy at the muscular level with increasing intensity (Clarys & Cabri, 1993; Hug & Dorel, 2009). While only a few studies have investigated changes in muscle coordination between different effort levels in swimming, more research has been conducted in other dynamic sports with different outcomes. For example, coordination among the major lower-limb muscles changed considerably with increasing running speed (Komi, Gollhofer, Schmidtbleicher, & Frick, 1987; Kyröläinen, Avela, & Komi, 2005), while in rowing ergometer studies, Turpin, Guével, Durand, and Hug (2011) found no dramatic modifications in the timing of activation or in the shape of individual EMG patterns, but significant changes in the level of muscle activity with increased power output. Compared to these land-based sports, swimming involves principles of hydrodynamics that might alter the muscle coordination with different effort levels. These are primarily related to resistance/drag, lift and buoyancy forces in the water. Water offers substantially more resistance to movement than air and form drag increases by the square of the velocity (Lyttle, Benjanuvatra, Blanksby, & Elliott, 2002). Velocity also tends to increase the "upward lift" because of the upward force exerted by the water that swimmers push downward as they pass through it (Maglischo, 2003). Clarys et al. (1988) found an increase in normalized intensity and number of contraction peaks in four arm and shoulder muscles when swimming speed increased in front crawl. Rouard, Quezel, and Billat (1992), however, found greater muscular activations at 75% and 100% and lower recruitment at 85% and 95% of swimmers' best performance in the 100 m front crawl. However, it is also important to know whether different effort levels alter the muscle coordination and activation patterns in contemporary breaststroke swimming. Such knowledge could then be used by coaches to tailor the intensity of technique and endurance training and to work on movement economy.

In order to find the optimal muscle activation and coordination pattern it is necessary to assess it in the world's best swimmers. Coactivation between muscles is also generally involved in the processes of determining movement efficiency, safety, control of the precision and velocity of movement, and for stabilizing single joints (Basmajian & De Luca, 1985; Frost, Dowling, Dyson, & Bar-Or, 1997; Neumann, 2010). While coactivation is necessary during certain movements (Draganich, Jaeger, & Kralj, 1989), excessive activation in antagonist muscles is associated with increased metabolic cost and an inefficient use of energy (Frost, Bar-Or, Dowling, & Dyson, 2002; Hortobágyi, Finch, Solnik, Rider, &

DeVita, 2011; Huang, Kram, & Ahmed, 2012) which could lead to an earlier onset of fatigue and be detrimental to performance. Therefore, it is important to know whether there are differences in muscle activation, coordination and coactivation between swimmers at different performance levels that could be identified as performance discriminators. Such knowledge is also important to provide coaches and swimmers with the most relevant key points for these variables and 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.

2. Theoretical framework

2.1 Breaststroke swimming

The history of breaststroke swimming dates back 6000-9000 years to the "Cave of swimmers" in Wadi Sura, which was explored by (László, 1934). Here, humans performed a frog-like action with the legs to move through the water. The first swimmer to cross the English Channel in 1875, Captain Matthew Webb, used breaststroke. Breaststroke is also considered the first competitive swimming style after the Middle Ages and the other competitive strokes have evolved from it (Maglischo, 2003). It was first in the Olympic program as a standalone discipline in 1904. For international championships the competitive distances are 50, 100 and 200 m with durations of about 25-27 s (males) and 29-31 s (females), 55-60 s (males) and 62-65 s (females) and 120-130 s (males) and 134-140 s (females) depending on the length of the pool.

Breaststroke consists of a dynamic and cyclic motion where both the upper and lower limbs as well as the trunk simultaneously move in complex manners to generate forward propulsion. It also has the lowest mean velocity of the four competitive swimming strokes (Chengalur & Brown, 1992; Craig, Skehan, Pawelczyk, & Boomer, 1985; Leblanc, Seifert, Baudry, & Chollet, 2005), mainly because of the large intra-cyclic velocity variations (IVV) (Maglischo, 2003; Seifert, Leblanc, Chollet, Sanders, & Persyn, 2011), corresponding to the alternation of resistive and propulsive actions (Mason et al., 1989). While the other competitive strokes lose about 1/3 of their forward velocity during the recovery phases, some breaststrokers come to an almost complete stop during their leg recovery (Maglischo, 2003). This is because the body is often at steep angles to the forward movement, and both the arm and leg recovery occur mainly under water. Therefore performance in breaststroke swimming is highly linked to minimizing these velocity variations during the stroke. Among the four competitive swimming strokes, breaststroke is the one where the major source of propulsion is generated in the cyclic and simultaneous movement of the lower limbs during the leg kick (Mason, Patton, & Newton, 1989; Vilas-Boas, 1996). The main component of the breaststroke kick is flexion-extension in the sagittal plan (Lauer, 2013).

Throughout the history of competitive breaststroke swimming there have been many variations in techniques due to rule changes. In 1934 David Armbruster found that bringing the arms over the water during the recovery led to less resistance and improved speed. In the 1936 Olympics breaststroke was swum by some competitors with the arms brought over the water in a butterfly-like technique with the breaststroke kick. This technique led to butterfly becoming a separate stroke in 1952. In the 1950s breaststrokers began to swim underwater and in the 1956 Olympics Furukawa won the gold medal in the 200 m breaststroke by swimming as far as he could under water after the start and after each turn before emerging. In the 1960s many experts believed that the breaststroke should be performed with a flat body position on the surface of the water to avoid excess up-and-down movements throughout the SC (Colwin, 2002).

In the 1970s an undulating style of breaststroke was introduced, with a body undulation similar to butterfly. The style did not really catch on until FINA implemented several major rule changes in 1987 and later, which permitted swimmers to drop their head beneath the water surface during parts of each SC and to break the water surface with their hands during arm recovery. With this new motion, many swimmers felt that they achieved a better streamlined position during the leg kick phase since they could place the head down between the arms and execute the gliding phase underwater. In addition the wave action of the water can be utilized to create propulsion during the recovery of the arms and legs (Maglischo, 2003). Swimmers then experimented with different degrees of undulation, from a style resembling the old flat breaststroke “with no undulation” and a streamlined glide to techniques implementing extreme degrees of undulation (Colman et al., 1992; Persyn, Colman, & Van Tilborgh, 1992; Van Tilborgh, Willems, & Persyn, 1988). This has led to breaststroke today being known for having the most individual styles of all the competitive strokes and four distinct breaststroke techniques are identified: vertical, flat, undulating and undulating with arm recovery over the water (Maglischo, 2003). In addition, three coordination modes have been observed in breaststroke based on the glide time between the arms and the legs: glide (the body stays streamlined before the arm outsweep); continuous (the arm outsweep begins just as the leg kick finishes); and superposition (the arm outsweep begins before the leg kick finishes) (Maglischo, 2003). The techniques 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 a body-undulating breaststroke also known as dolphin breaststroke and wave breaststroke. Today, this new technique seems to be used by almost every competitive breaststroker with different degrees of undulation.

2.2 Body undulation during breaststroke

As already stated there are two main breaststroke techniques: flat and undulating. The flat breaststroke is characterized by a horizontal body position where the hips remain at or near the water surface throughout the entire SC. The breathing is executed by lifting and lowering the head while keeping the shoulders underwater so that the horizontal body position is not disturbed. In contrast, in the undulating breaststroke the head and shoulders are lifted out of the water to breathe while the hips simultaneously are lowered during the leg recovery. According to Seifert et al. (2011), there are four primary technical characteristics that separate the undulating from the flat breaststroke:

1) a deeper leg extension followed by an undulation raising the feet during the insweep;
2) hands and head dive under water during the arm recovery;
3) during the outsweep of the hands and insweep of the feet an upward arm trajectory causes the hand and foot movements to occur much more in the vertical axis rather than the horizontal;
4) during the leg propulsion the upper body dives forward and downward into the water, causing a dome-shaped body position. This is the essential part in the body undulating breaststroke, indicating a superposition of the end of leg propulsion and the beginning of the outsweep of the hands.

Sanders, Cappaert, and Pease (1998) note that the undulating breaststroke is distinguished by high shoulder action and a forward lunge of the upper body across the top of the water during the recovery phase of the leg kick. Trunk rotation around the transverse axis is quite distinct for the body undulating style and produces vertical movement in the head and shoulders, giving a characteristic "S" position when the legs are ending their propulsion (Seifert et al., 2011). It has also been noted that the relative phase durations and body angles change between the flat and undulating styles.

As in butterfly, there is a negligible potential for body roll in breaststroke. Therefore, undulating breaststroke has received increased importance in order to generate forward propulsion through undulation as well as to reduce form drag (Maglischo, 2003; Troup, 1999). Breaststrokers with different degrees of undulation and flat styles have been investigated by several researchers (e.g. Colman et al., 1998; Sanders, 1996; Sanders et al., 1998; Soons et al., 2003). Sanders et al. (1998) found that modern breaststroke was somewhat similar to butterfly in upper body movement, but the wave from the hips to ankle was too slow to generate propulsion. They also found in their Olympic breaststrokers that the two best ranked swimmers had the largest range of vertical hip motion. Performing breaststroke with a more pronounced body waving and trunk flexing decreased the IVV (Colman et al., 1998; Persyn et al., 1992; Sanders et al., 1998; Silva, Colman, Soons, Alves, & Persyn, 2002; Van Tilborgh et al., 1988). Colman et al. (1998) also found that the most extreme swimmers in terms of body undulation had considerably smaller differences between the maximum and minimum velocity peaks of CM due to movements of the body parts above the water surface creating a transfer of momentum.

Physical characteristics for the two styles have also been described (Colman et al., 1992; Persyn et al., 2000). Colman et al. (1992) found that specific muscle strength in order to produce strong leg kick and arm pull was more dominant in the flat style and more typically used by men, while the undulation technique required specific flexibility and was more typically used by women. The most recent studies on body undulation in elite swimmers were conducted more than 10 years ago and technical characteristics may have changed regarding undulation among elite swimmers.

2.3 Kinematic analyses

Kinematic analysis is the study of bodies in motion; it describes and quantifies the linear and angular positions of bodies without regard to the causes of the motion (Robertson & Caldwell, 2004). Every planar displacement is either a translation (rectilinear and curvilinear) or a rotation. Kinematics are often expressed in the context of motion in two-dimensional space (2D) or three-dimensional space (3D). Many of the same methods apply to both analyses and today a variety of systems are available to analyze sporting techniques to highlight the biomechanical factors that are determining and limiting athletic performance. Kinematic analyses can quantify and determine swimming stroke mechanics both in over- and underwater movements. Kinematic data are predominantly gathered from the use of imaging and motion-caption systems that record the motion of markers attached to a moving subject, followed by interactive tracking or automatic tracking to acquire the coordinates of the markers (Robertson & Caldwell, 2004).

2.3.1 Kinematic analysis through motion capture

Today, the two methods for tracking information from motion capture are interactive tracking and automatic tracking. Interactive tracking relies on the researcher manually following the subject frame by frame through the motion while identifying markers on the participant’s body. Automatic tracking uses computer algorithms to identify and track small reflective markers attached to the individual through the movement. The solution is then composed from all the information obtained from the cameras and post-processing of the data enables the calculation of 3D rotations (joint angles) of each segment. Automatic tracking is based on the program identifying paths that move significantly differently than the paths around the subject and removing interference (e.g. reflections). There will still be instances where manual intervention is needed in order to guide the program through the motion (e.g. losing sight of a marker, including the effects of reflection).

In swimming, kinematic analyses have until recently been performed using motion capture in 2D with interactive tracking of body markers. For some time, different body parts have been manually digitized from 2D motion capture to create 3D models using computer software (e.g. Payton, Bartlett, Baltzopoulos, & Coombs, 1999; Payton, Baltzopoulos, & Bartlett, 2002; Takagi, Sugimoto, Nishijima, & Wilson, 2004) and recently full 3D underwater motion capture of swimming movements has been described and used (e.g. Figueiredo, Barbosa, Vilas-Boas, & Fernandes, 2012; Figueiredo, Kjendlie, Vilas-Boas, & Fernandes, 2012; McCabe, Psycharakis, & Sanders, 2011; McCabe & Sanders, 2012;

Psycharakis, Naemi, Connaboy, McCabe, & Sanders, 2010; Puel et al., 2012). Psycharakis and Sanders (2009) digitized 19 body markers for 6 underwater cameras capturing at 50 hertz (Hz) with approximately 1 s per SC for 10 swimmers, adding up to roughly 57,000 manually digitized points. Although some subtractions can be made for markers that are not visible in all cameras and positions, there is no questioning that manual digitization is a very tedious process and has room for potential human errors.

In dry-land laboratories, 3D motion capture with automatic tracking of body markers has been a regular practice for many years and has provided scientists, coaches and athletes with valuable kinematic information (Figueroa, Leite, & Barros, 2003; Josefsson, Nordh, & Eriksson, 1996; Richards, 1999). Today, several companies offer the necessary technology for dry-land measurements (e.g. SIMI Motion, Qualisys, Vicon and ARENA). For automatic tracking to work underwater there are several confounding factors that need to be considered, including: light conditions that often make it hard for the program to distinguish between reflections from the markers and reflections from light coming onto the pool; bubbles; and the fact that infrared cameras do not capture images in water. Recently, new underwater systems and software have been developed by commercial and non-commercial companies to facilitate the use of automatic tracking for 3D underwater motion capture, such as Qualisys, SIMI Reality Motion Systems and CAST technique. Recently, this new technology for 3D underwater motion capture in water with automatic tracking was used to investigate the IVV and velocity in breaststroke swimming (Olstad, Zinner, Haakonsen, Cabri, & Kjendlie, 2012; Olstad, Zinner, Cabri, Haakonsen, & Kjendlie 2012). The greatest benefit of 3D automatic tracking is the time saved in processing the data. It opens up possibilities for conducting wide-scale studies that can investigate differences in kinematics across groups and levels of swimmers. It can also provide coaches and swimmers with “real-time” feedback and better accuracy for improvements in technique.

2.3.2 Swimming kinematics

Kinematic analysis of swimming movements have a long history, from the earliest published work “Colymbetes” by Nicolas Wynman in 1538 for learning breaststroke, to “The Art of Swimming” by Melchisédech Thévenot in 1696 describing a type of breaststroke similar to the modern style, the first recording of swimmers under water in 1928 by David Armbruster, and the book “The Science of Swimming” (Counsilman, 1968) which laid the foundations for many studies to come. Kinematic analyses of performance variables such as swimmers’ displacement, velocity and acceleration, body and joint angles, and spatial location have been conducted. The most common stroke kinematics today are 1) SC kinematics; 2) limb kinematics; and 3) hip and center of mass kinematics (Barbosa, Marinho, Costa, & Silva, 2011).

2.3.2.1 *Stroke cycle kinematics*

Basic SC kinematics such as velocity, SR and stroke length (SL) have been carried out since the 1970s (e.g. Craig & Pendergast, 1979; East, 1970). Today, there are many different ways of identifying the beginning of an SC in breaststroke, including each time the swimmer's head comes up to breathe, when the arms are extended in a streamlined position, when the leg kick begins its propulsive phase or when the feet are squeezed together and the legs are in a streamlined position.

2.3.2.2 *Stroke length, stroke rate, velocity and stroke index*

Mean swimming velocity is regarded as the best parameter for evaluating swimming performance (Barbosa et al., 2011; Craig et al., 1985) and is the product of SR and SL (Smith et al., 2002). Stroke length is defined as the horizontal distance the body travels during a complete SC (distance per stroke) (Barbosa et al., 2011). Stroke rate or stroke frequency is defined as the number of complete SCs per unit of time (per min or per s), usually expressed as strokes$\cdot$min^{-1} or in Hz (Barbosa et al., 2011). Therefore, an increase or decrease in velocity comes from an increase or decrease in SR and/or SL (Craig et al., 1985; Kjendlie, Haljand, Fjortoft, & Stallman, 2006; Toussaint, Carol, Kranenborg, & Truijens, 2006). According to Craig et al. (1985) velocity can be increased in five different ways:

1) increase SL and reduce SR,
2) increase SL while maintaining SR,
3) increase both SL and SR,
4) increase SR while maintaining SL, and
5) increase SR and reduce SL.

Increasing both SL and SR will give the greatest improvement in velocity, while increasing SR and reducing SL can only improve velocity to a certain extent. Stroke length relies more on technical skills (Chollet, Pelayo, Delaplace, Tourny, & Sidney, 1997; Seifert, Boulesteix, Carter, & Chollet, 2005) while SR relies more on neuromotor and energetic processes in the body (Wakayoshi, D'Acquisto, Cappaert, & Troup, 1995). Studies have identified SL as being more important than SR in improving velocity (Craig et al., 1985; Hellard et al., 2008). However, Mason and Cossor (2000) found no or weak relationships between SR, SL and performance for top-level international swimmers at the Pan Pacific Championships and Pai, Hay, and Wilson (1984) found that elite swimmers reached similar velocities, but with very different combinations of SL and SR. This supports the theories of Craig and Pendergast (1979) and Maglischo (2003) that the relationship between velocity, SL and SR is an inverted U, where it is not possible to maintain a high SL simultaneously with a high SR (Figure 1. *The relationship between stroke rate (SR), stroke length (SL) and velocity.*). Therefore, the highest possible velocity is the result of an optimal distribution between SL and SR that is individual to the swimmer. In breaststroke, an increase in velocity comes from an increase in SR, but the SL decreases more than in all of the other strokes (Craig & Pendergast, 1979). Throughout a swimming competition, decrease in velocity is highly related to a decrease in SL for all strokes (Hay & Guimarães, 1983) and the highest SR is most commonly found during the last lap (Letzelter & Freitag, 1983). In addition, a higher velocity can be achieved from reducing resistance to forward motion by perfecting a position of low resistance.

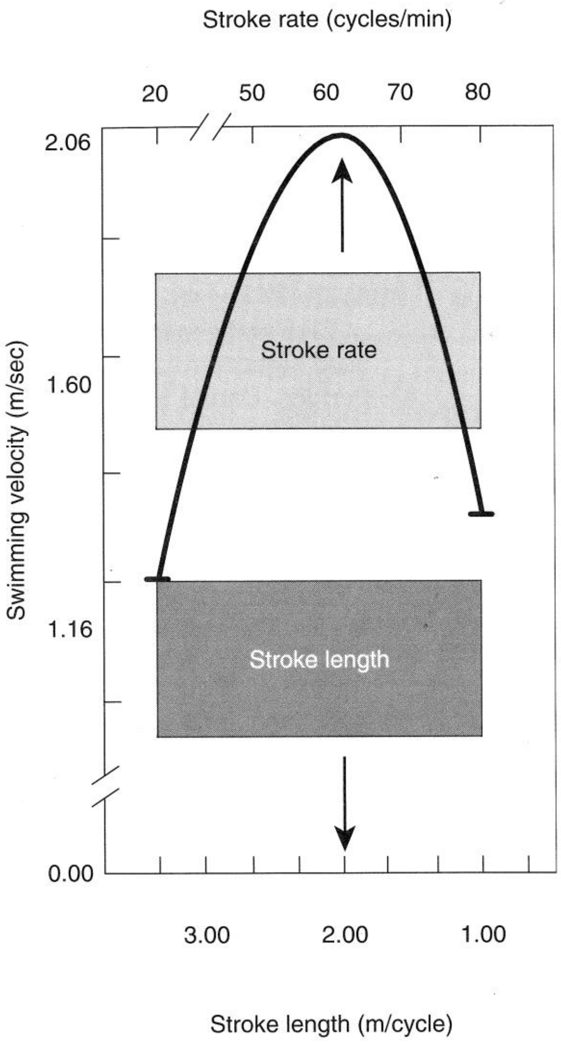

Figure 1. The relationship between stroke rate (SR), stroke length (SL) and velocity.
The fastest velocity for any particular race distance is achieved by using an individual optimum combination of SR and SL.
Reprinted, with permission, from E.W. Maglischo, 2003, *Swimming fastest* (Champaign, IL: Human Kinetics), 699.

Stroke index (SI) is another parameter used to classify SC kinematics and determine how effective the overall technique is. According to Costill, Kovaleski, Porter, Fielding, and King (1985), SI can be used to estimate overall swimming efficiency. The theory implies that at a given velocity the swimmer with the longest SL will swim most efficiently. Among the four competitive strokes, crawl has the highest SI, followed by backstroke and butterfly, with breaststroke being the least efficient stroke (Sánchez & Arellano, 2002).

2.3.3 Breaststroke phases from a practical and scientific point of view

Stroke cycle kinematics have some limitations in terms of developing strategies for improving performance. Therefore, more advanced methods and biomechanical equipment have been developed to quantify other kinematic parameters related to swimming performance (Alberty, Sidney, Huot-Marchand, Hespel, & Pelayo, 2005). A further breakdown of the stroke into smaller phases is therefore needed in order to better understand what occurs during the SC with different techniques and coordination modes to identify potential performance discriminators. Different stroke phase divisions have already been used within the practical and scientific community in order to understand and describe breaststroke kinematics and movements. These phase divisions are often composed of phases relating to arm pull and leg kick.

2.3.3.1 Breaststroke phases from a practical point of view

From a practitioner's point of view the stroke has been divided into phases in order to teach and learn breaststroke movements. Every SC should start and stop in a streamlined position which should at least be held for a fraction of a second (Mark, 2015). Then the SC continues with an arm pull which is a short semicircular pull and which is described as an oval shape or the shape of a reverse heart. The arm pull is often divided into three or four phases as illustrated in Figure 2:

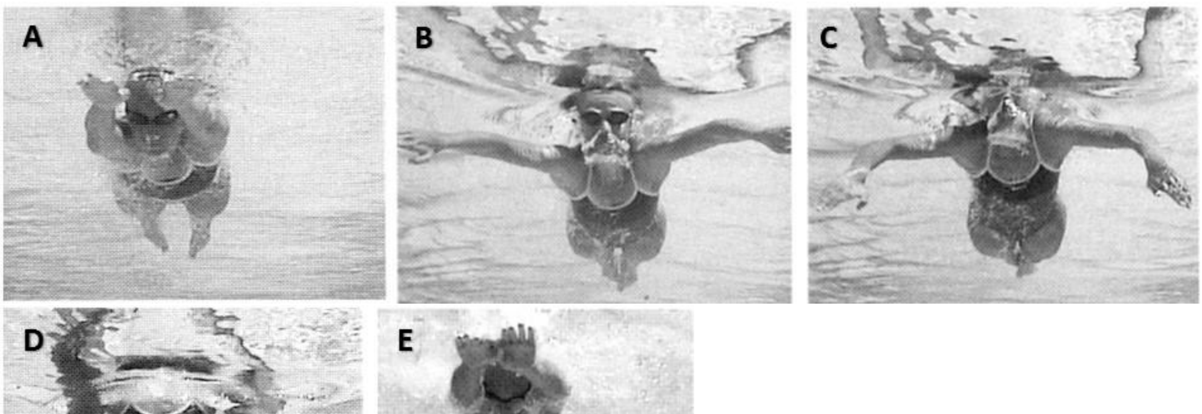

Figure 2. The breaststroke arm pull from front view.
(A) outsweep begins; (B) catch; (C) mid insweep; (D) recovery begins; and (E) arm pull finished.
Adapted, with permission, from E.W. Maglischo, 2003, *Swimming fastest* (Champaign, IL: Human Kinetics), 234-235.

A) outsweep: from a streamlined position the palms turn outward, forward and upward in a slow sculling motion;

B) catch: in which the arms go beyond the shoulder width and the palms change direction to point backwards while facing towards the bottom of the pool;
C) insweep: where the arms still travel slightly outwards initially to overcome inertia, before a lift is generated with high elbows. The first part of the insweep is then completed at approximately the vertical plane through the shoulders. Towards the end of the insweep the hands come together with palms facing in front of the chest at high hand speed and with the elbows at the side of the body;
D) recovery: hands and arms are extended forward into a streamlined position with the head down in the water;
E) arm pull finished: arms and upper body are back into a streamlined position.

The main goal of the arm pull is to generate propulsion and set up the rest of the stroke. This is in contrast to the other strokes in which the palms or arms are never pushing water straight backwards (Mark, 2015). According to Mason et al. (1989) the arm propulsion starts during the outsweep and finishes around the middle of the insweep, where the hands are coming together under the shoulders and the backward direction of the hands changes to forward, but variations may occur depending on the hand path. The main goal of the insweep is to generate maximum thrust and the goal of the recovery is to minimize drag.

The leg kick has various names, including wedge kick, pros kick, frog kick and wave kick, but is most often described as a whip kick (Maglischo, 2003) because when executed correctly, the kick has a whip-like motion starting at the core and moving down through the legs. The leg kick is often divided into four phases and can be seen in Figure 3.

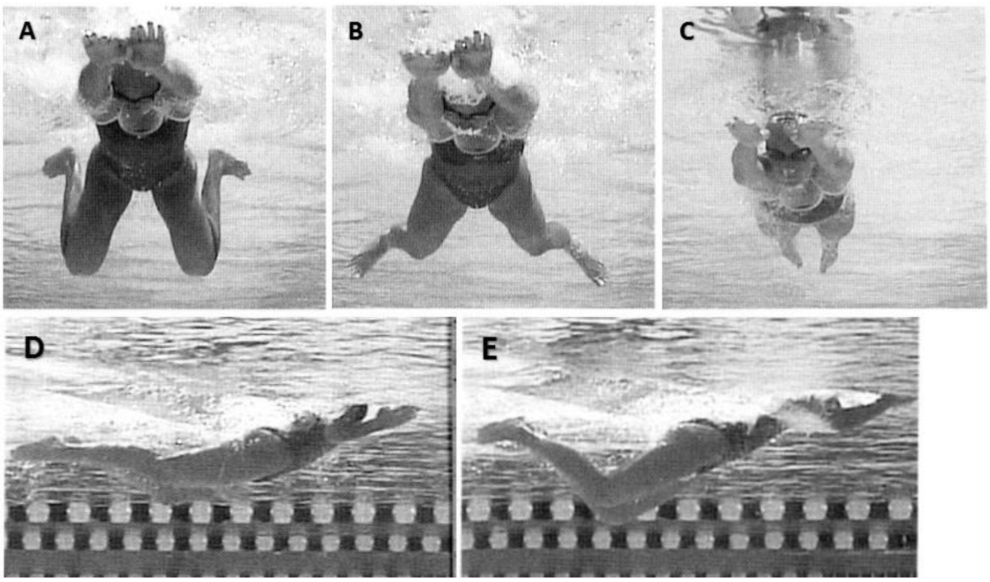

Figure 3. The breaststroke leg kick from a front view (upper row (A, B, C)); and a side view (lower row (D, E)). (A) leg propulsion begins; (B) insweep begins; (C) glide begins; (D) knee flexion of leg recovery begins (wave propulsion); and (E) hip flexion of leg recovery begins (wave propulsion finished).
Adapted, with permission, from E.W. Maglischo, 2003, *Swimming fastest* (Champaign, IL: Human Kinetics), 232-235.

A) propulsion: begins from the smallest knee angle with the feet in dorsiflexion to ensure grip on the water, allowing a large propulsive motion during the push from the leg extension that starts slowly and rapidly accelerates towards the insweep;
B) insweep: the feet squeeze the legs together and sometimes into an upward motion with high feet velocities and a streamlined position;
C) glide: the legs are in a streamlined position and swimmers execute different types of body undulation, which is also present throughout the SC, but here it is more precise in order to preserve and create velocity (upward motion of the legs);
D) knee flexion of leg recovery: the legs are flexed at the knees to start the recovery;
E) hip flexion of leg recovery: brings the feet towards the posterior (buttocks) with as little active drag as possible during the hip flexion. Therefore, the knees stay relatively close together and should not go too deep.

When breathing is executed correctly it comes naturally during the arm insweep. Here the elbows have reached the line of the eyes and remain at the same depth while the hands may press deeper to support the height of the upper body. The lift in the upper body allows the chest, shoulders and upper back to automatically lift up.

2.3.3.2 Breaststroke phases from a scientific point of view

The practical way of dividing the breaststroke into phases has some limitations for scientific research. Therefore, many researchers have used a qualitative method involving video analysis to identify stroke phases (e.g. Chollet, Seifert, Leblanc, Boulesteix, & Carter, 2004; Leblanc et al., 2005; Leblanc, Seifert, & Chollet, 2009; Seifert & Chollet, 2005) while others have reconstructed the stroke in 3D using interactive tracking of body markers for the pulling pattern (e.g. Schleihauf, 1979; Silvatti et al., 2013) or using 3D automatic tracking for the leg kick (Guignard et al., 2015b) or full body breaststroke (Lauer, 2013). Angular positions were used to define different stroke phases in a number of studies (e.g. Nemessuri & Vaday, 1971; Persyn et al., 1992; Soons, Silva, Colman, & Persyn, 2003) while others determined the IVV from the center of mass in 3D (e.g. Colman, Persyn, Daly, & Stijnen, 1998; Costill & D'Acquisto, 1987; Maglischo, Maglischo, & Santos, 1987) or from a speedometer attached to the hip (e.g. Costill & D'Acquisto, 1987; D'Acquisto & Costill, 1998; Leblanc, Seifert, Tourny-Chollet, & Chollet, 2007).

When assessing the relative stroke phase durations a model incorporating four phases (arm propulsion, leg recovery, leg extension and glide) is often applied (Chollet et al., 2004; D'Acquisto & Costill, 1998; Sanders, 1996). When velocity increases the phase durations change, with the glide phase showing the most variability (Sanders, 1996).

In simultaneous strokes such as breaststroke and butterfly the arm-leg coordination is often used to interpret inter-limb coordination. Dividing the arm stroke and leg kick into phases has allowed researchers to study motor patterns and inter-limb coordination.

The first studies in swimming looking at stroke phases and inter-limb coordination were by Vaday et al. (1971) in front crawl and Nemessuri et al. (1971) in breaststroke. Nemessuri et al. (1971) modelled breaststroke by dividing the cyclic pattern and distinct angles in the stroke into four main phases: glide, arm propulsion, arm and leg recoveries and leg propulsion. Since then, several authors have studied motor patterns and inter-limb coordination in breaststroke (e.g. Chollet et al., 2004; Chollet, Tourny-Chollet, & Gleizes, 1999; Leblanc et al., 2009; Sanders, 1996; Seifert & Chollet, 2005; Soares, Sousa, & Vilas-Boas, 1999). These authors analyzed the spatial-temporal relationships between the key positions defining the start and the end of each arm and leg stroke phase.

A recent method to analyze breaststroke phases was developed by Chollet et al. (2004), who identified five phases for both arms and legs and measured the time gaps between the phases using a speedometer-video. These five phases of the breaststroke leg kick are identified as: propulsion, insweep, glide, first part of the recovery until a thigh/leg angle of 90° is reached, and second part of the recovery. Chollet et al. (2004) and Seifert and Chollet (2005) applied this method to analyze the flat style breaststroke and proposed a new index for arm and leg coordination in elite and recreational swimmers. The challenge with this method for analyzing the breaststroke kick in terms of phases is the assumption that all breaststroke kicks finish with the feet actively coming together during the insweep followed by a streamlined glide and active knee bend to start the recovery. In today's contemporary breaststroke swimmers the technique influences both the insweep and knee bend during the leg recovery phase. Instead of a more traditional up, out, in and glide type of kick, some swimmers now perform a more rounded kick where the feet are not always actively pushed together during the insweep, but into an up-kick motion and changes in the knee angle are observed during the gliding phase. Today, there is no specific index for the body undulating breaststroke or a specific method for analyzing the leg kick that encompasses all the different styles of breaststroke. Therefore, a specific method for breaking the breaststroke leg kick into phases that cover all the different styles is needed.

Resistive and propulsive forces act on the swimmer’s body and represent the variations in instantaneous velocity during an SC (Miller, 1975). Intra-cyclic velocity variations within an SC are therefore pertinent parameters for characterizing swimming technique through biomechanical and coordinative development (Vilas-Boas, Barbosa, & Fernandes, 2011) and have been studied by several researchers (e.g. Alberty et al., 2005; Alves, Santos, Veloso, Correia, & Gomes-Pereira, 1994; Capitão et al., 2006; Holmér, 1979; Miyashita, 1971; Vilas-Boas, 1992; Vilas-Boas, 1996). Intra-cyclic velocity variations characterize the accelerations and decelerations of a swimmer through a fixed body point (normally the hip) or the body's center of mass (CM) within an SC (Fernandes, Ribeiro, Figueiredo, Seifert, & Vilas-Boas, 2012). The efficiency of a swimmer can also be quantified by the forward velocity variations (Rouard, 2011).

Intra-cyclic velocity variations are most frequently calculated from either a fixed point (hip), using mechanical, image-based or mixed methods (e.g. Craig, Termin, & Pendergast, 2006; Maglischo et al., 1987; Schnitzler, Seifert, Alberty, & Chollet, 2010), from 2D and 3D image reconstruction of the CM through manual digitizing procedures (e.g. Barbosa, Fernandes, Morouco, & Vilas-Boas, 2008; Maglischo et al., 1987; Psycharakis et al., 2010) and recently with 3D automatic tracking from a fixed point (hip) (Olstad, Zinner, Haakonsen, Cabri, & Kjendlie, 2012). The methods using a fixed point present the horizontal velocity curve of that point through the SC. During the SC, the CM typically moves around within the abdomen (Cohen, Cleary, Harrison, Mason, & Pease, 2014). 2D and 3D reconstruction of CM therefore define the body based on different anatomical markers applied to models for calculating the CM through the SC. Twenty-one body reference points were used by Lauer (2013) in breaststroke and Fernandes et al. (2012) in front crawl to define such a 3D model.

The advantages of using a mechanical procedure focused on a fixed point are that the results and outputs can provide immediate practical information and that the procedure is very simple and less time consuming (Vilas-Boas et al., 2011) and can easily take multiple SCs into account. The same advantages have also been found using 3D motion capture with automatic tracking (Olstad et al., 2012). However, conflicting results have been presented regarding the accuracy of IVV calculated from a fixed point versus CM. In breaststroke several studies (Capitão et al., 2006; Costill & D'Acquisto, 1987; Maglischo et al., 1987) found good correlations between the two, while in front crawl (Fernandes et al., 2012; Psycharakis et al., 2010; Psycharakis & Sanders, 2009) and butterfly (Barbosa, Santos Silva, Sousa, & Vilas-Boas, 2003; Mason, Tong, & Richards, 1992) analyses found that a fixed point may not properly represent the CM. Disadvantages for calculating and using CM are that the process is very time-consuming (Maglischo et al., 1987), depends on the accuracy of the anthropometric biomechanical model used for calculating the inter-limb inertial effects (Schnitzler et al., 2010), may involve errors from digitizing procedures and underwater video techniques (Barbosa et al., 2008; Figueiredo, Vilas-Boas, Mala, Goncalves, & Fernandes, 2009), and usually allows only one SC to be analyzed (Fernandes et al., 2012), preventing analysis of inter-cycle variability.

Breaststroke possesses the greatest IVV of the four strokes due to the high drag component of underwater recovery for the arms and the legs. From the first studies investigating IVV in swimming the stroke was classified into four phases based on two velocity increases and decreases: 1) leg propulsion, increase; 2) middle or end of the leg insweep to the beginning of phase 3, decrease; 3) arm propulsion, increase; 4) arm and leg recoveries, decrease (Seifert et al., 2011). Studies in all four strokes have shown or suggested that lower IVV is associated with less energy cost (Barbosa et al., 2008) in breaststroke (Barbosa et al., 2006; Vilas-Boas, 1996), butterfly (Barbosa et al., 2005; Barbosa et al., 2006; Barthels & Adrian, 1971; Kornecki & Bober, 1978), front crawl (Alves, Gomes-Pereira, & Pereira, 1996; Barbosa et al., 2006; Nigg, 1983), and backstroke (Alves et al., 1996; Barbosa et al., 2006). Generally, large IVV variations lead to loss of mechanical output and horizontal velocity and IVV measurements can be an indicator of good technique and work economy.

Because of the large number of different phase divisions applied by practitioners and researchers it is difficult to decide on one ideal method. They all contribute to a better understanding of how breaststroke is performed and should be selected exclusively by the primary goal for the outcome, e.g. teaching breaststroke technique, analyzing SC kinematics, motor patterns, inter-limb coordination, IVV or muscular activation patterns.

2.4 Electromyography

For centuries the electrical activities of muscles have been investigated by scientists. The first documented experiment dealing with EMG dates back to Francesci Redi in 1666, who discovered a highly specialized muscle in electric ray fish that generated electricity (Biederman, 1898 cited in Basmajian & De Luca, 1985). Electromyography can be defined as an experimental technique used for studying muscle function through the detection, recording and analysis of myoelectric signals (motor action potentials) which produce contraction of the muscle fibers in the body (Basmajian & De Luca, 1985; Medved & Cifrek, 2011). Electromyography is often used to observe muscle activity and electromyographic recordings are used to quantify the amount of muscle activation in both static and dynamic contractions. However, the EMG signal can be difficult to interpret due to the many factors that can affect it. This can include the motor unit size, the number of motor units recruited, the motor unit recruitment strategy, fiber-type (slow twitch versus fast twitch) composition of the muscle, the instrumentation used to detect the signal, and the electrode placement (Kamen & Caldwell, 1996; Roberts & Gabaldon, 2008). Applications for the use of EMG include gait analysis, biofeedback and clinical diagnosis for neuromuscular disorders. Within the branch of kinesiology, EMG has been used for reporting the action timing of specific muscles in various movements (coordination, synchronization, intensity and contribution) between muscles, to estimate the force produced by the muscle, muscular fatigue during exercise, spinal reflexes, rehabilitation and ergonomic design. Electromyography is primarily conducted using two types of electrodes: surface electrodes (noninvasive, directly placed over the muscle on top of the skin), either in the form of monopolar, bipolar or linear electrode arrays, or with intramuscular electrodes (invasive needles or wires that are inserted through the skin and directly into the muscle tissue) (Merletti & Farina, 2009). Surface electrodes are commonly used in kinesiological EMG studies because of their noninvasiveness. Therefore, EMG conducted with surface electrodes is the only method that will be thoroughly introduced and referred to as EMG.

2.4.1 Surface electrodes, preparation and placement

A further detailed presentation of recommended surface electrodes, preparation and placement is described in *Study 1*.

2.4.2 Signal recording

The following recommendations for signal recording are primarily based on the European recommendations for surface electromyography (SENIAM project) (Hermens et al., 1999) and The International Society for Electrophysiology and Kinesiology (ISEK) (Merletti, 1999).

A signal needs to be sampled at a frequency higher than twice that of the highest harmonic of interest in order to prevent loss of information in the signal. This is referred to as the Shannon and Nyquist Theorem. In order to prevent “aliasing” when reconstructing a complex analog signal (sinusoid) the signal must be sampled at no less than twice its frequency. Ninety-five percent of the harmonics in the power spectrum of the EMG signal are below 400 Hz. The remaining 5% is for the most part considered electrode and equipment noise (Hermens et al., 1999). Therefore the sampling frequency is normally 1000 Hz and the cut-off point is close to 500 Hz. The voltages recorded are relatively small, often below 5 mV for surface EMG. Therefore special instrumentation is needed to record them (Winter, 2005) and amplifiers are commonly used. According to Kamen and Gabriel (2010a) the essential components of an amplifier are: 1) gain; 2) input impedance; 3) common mode rejection ratio; and 4) frequency response of the amplifier relative to the acquired signal.

When recording EMG signals we often encounter movement artifacts and some instability of the electrode-skin interface. Therefore, amplifiers contain analog filters designed to eliminate these unwanted frequencies in the recording. Guidelines from the SENIAM project recommend high-pass filters with 10-20 Hz cutoff and low-pass filters near 500 Hz cutoff (Hermens et al., 1999) while ISEK recommend 5-10 Hz and 500 Hz respectively (Merletti, 1999). The cutoff frequencies depend on the nature of the signal and are therefore often set between 10 and 500 Hz (Kamen & Gabriel, 2010a). The high-pass cutoff is used for removing artifacts associated with electrode and cable movements while the low-pass cutoff is used for minimizing the signals picked up by the electrode from the surroundings.

2.4.3 Signal processing

The raw EMG signal contains the most complete information, but needs to be processed in order to provide useable information. Today there are many types of signal processing available, e.g. raw, half-wave rectified, full-wave rectified, filtered, averaged, smoothed, integrated, root-mean-square (RMS), frequency or power spectrum, fatigue analysis, number of zero-crossings, amplitude probability, distribution function, conduction velocity and wavelet. Some of the most common signal processing techniques are described in Table 1. These processing techniques are often classified into amplitude, timing and frequency (Kamen & Gabriel, 2010b). Amplitude measurements on the skin are considerably affected by the thickness and conductivities of the skin, subcutaneous layers, the relative position between the electrodes, intervention zones and tendons of the active motor units, and properties of the electrodes (Merletti, 1999). According to Farina (2006) the interpretation of dynamic EMGs is more complicated than the interpretation of static contractions. The signal is significantly less stationary in dynamic contractions where recruitment and decruitment of motor units and joint angles change at a faster pace. This leads to a relative shift of the electrodes on the skin with respect to the origin of the action potential (Farina, Merletti, Nazzaro, & Caruso, 2001), and changes in the conductivity properties of the tissues separating electrodes and muscle fibres. Filtering of the EMG signal may therefore occur at two points during the processing. The first point occurs after the measurement is conducted and the second one during the creation of the linear envelope (Shiavi, Frigo, & Pedotti, 1998).

Table 1

Common methods of electromyographic signal processing in dynamic and isometric exercises

Method	Purpose	How
Raw (with or without band-pass filtering)	Detects errors in the recording. Provides first objective information regarding the muscle innervation, "on-off" and "more-less" characteristics.	Samples 1000 Hz or higher, often band-passed filtered 10-500 Hz.
Full-wave rectified (absolute value)	Takes the absolute value of the raw signal. Intermediate step before another process (e.g. averaging, linear envelope, integration). Raw EMG has a mean value of zero.	Converts all negative amplitudes from baseline to positive.
Linear envelope	Detects onset of activity. Determines levels of contraction. Smooths the signal.	The full-wave rectified signal is either: a) Average rectified value (AVR): moving average, often 50-100 ms (range 20-500 ms) b) Root-mean-square (RMS): square root calculation, often 50-100 ms (range 20-500 ms) Higher ms provide more smoothing and higher risk of time shift in contractions with steep signal increase. c) Low-pass filter 4-10 Hz (e.g. Butterworth 2nd order or higher) cutoff
Ensemble average Average EMG	Creates muscle activation pattern. Represents contraction during cyclic activity. Compares among participants. Compares across experimental conditions.	Applied to the linear envelope with: a) Amplitude normalization: Maximal voluntary contraction (MVC), peak or mean value from the dynamic exercise b) Time normalization: All repetitions within the exercise are separated into an equal number of periods. The mean value for each period is calculated and averaged to form the ensemble average curve, usually expressed in % of the cycle or phase.
Peak, average peak, mean, minimum and slope	Measures amplitude	Full-wave rectification.
Integrated EMG (iEMG)	Establishes a quantitative relationship between EMG vs. force or EMG vs. work. Total muscular effort.	Mathematical integration of area under absolute values of EMG time series. RMS is similar, but does not require absolute values. Electronically requires full-wave rectification. Uses simple time integration, reset after a fixed time interval or reset after a particular value is reached. Amount of iEMG is computed from amplitude or differences between two amplitudes.
Frequency spectrum Mean and median frequency, Peak and total power	Determines onset of muscular fatigue. Detects neural abnormalities.	Calculated in the power spectrum with Fast Fourier Transformation (FFT). A series of frequency analyses (window 1 to 5 s, can overlap). Normalized to percentage of initial mean or median frequency. Decide a threshold for when fatigue occurs.

2.4.3.1 The raw electromyographic signal

The raw EMG signal is mostly used for detecting problems through visual inspection of the recording before further processing, such as ECG crosstalk (heart rate detection), AC interference (50 or 60 Hz depending on the country), DC-offset or -bias (baseline not at zero volts), muscle crosstalk, cable motion artifacts, skin-electrode interface or amplifier saturation (clipped at e.g. ± 2.5V).

2.4.3.2 Linear envelope

So-called linear envelope detection is the most commonly applied demodulation technique for extracting information from the waveform of the EMG signal (Kamen & Gabriel, 2010b). The raw EMG signal is first full-wave rectified (positive polarity) and then low-pass filtered in order to reduce artefacts in the signal (from 3 to 60 Hz, mostly set to under 20 Hz, but this depends on the goal of the study) to create the linear envelope (Figure 4). Low frequency noise can come from electrode motion artifacts in the form of disturbances of the electrode charge layer and deformation of the skin under the electrodes. The power density of these artifacts is mostly below 20 Hz. It is recommended to set the cutoff frequency based on retaining 95% of the power density in the selected movement in order to reduce EMG variability while minimizing signal distortion (Shiavi et al., 1998). The linear envelope is useful for cyclic motor tasks such as running, cycling and swimming, where a grand average of several EMG cycles of a given muscle is wanted (Felici, 2004) and additional smoothing is introduced through the averaging process of the measured cycles. Therefore the average linear envelope is commonly used for presenting the muscle activation profile (Frigo & Shiavi, 2004) and interpreting and detecting the onset and offset of muscular activity.

An alternative way of generating the EMG envelope is to compute the RMS value of the signal through a window that moves across the signal. Smoothing with a low pass filter with a given time constant (10-250 ms) is often described as "smoothing with a moving-average filter (low pass filter) with a time constant of x ms". Time constants higher than 25-30 ms may introduce detectable delays and should be used only when interest is focused on the mean amplitude (moving weighted average) and not on any timing relationship with other events (Merletti, 1999).

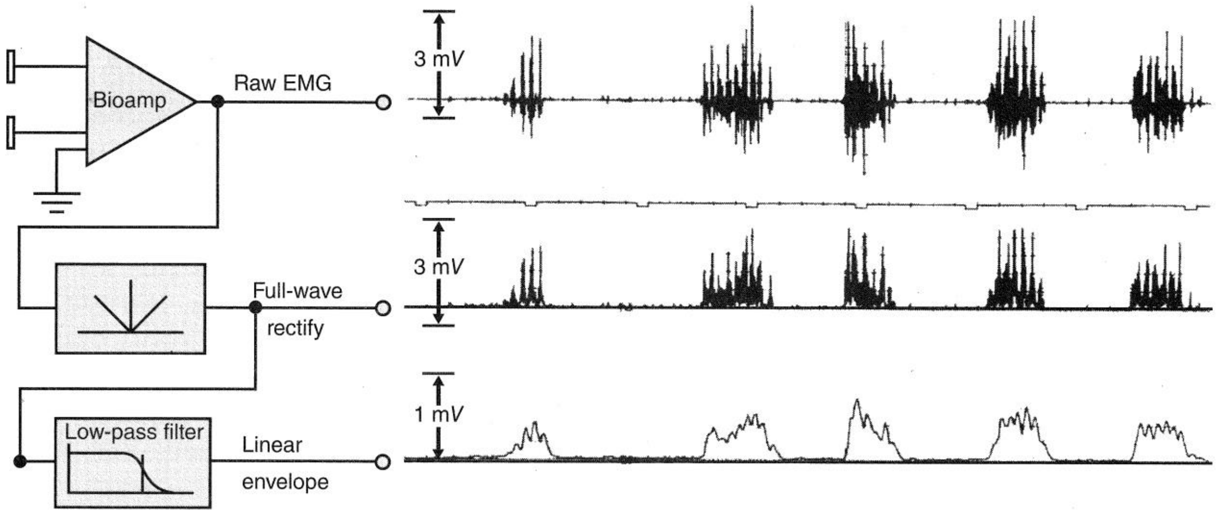

Figure 4. The steps involved in linear envelope detection of the EMG signal.
The top area shows the raw EMG signal. The first step is full-wave rectification (middle). The final step is low-pass filtering (bottom). To the left of the EMG waveforms is the engineering schematic of the steps depicted in the three panels.
Adapted, with permission, from D. A. Winger, 2005, *Biomechanics and motor control of human movement*, 3rd ed (Hoboken, NJ: John Wiley & Sons), 250.

2.4.3.3 Amplitude analysis

The amplitude of the EMG signal is used to interpret the neural drive to the muscle (Kamen & Gabriel, 2010b). When viewing the EMG signal in real time the amplitude is roughly proportional to the force applied in the muscle. However, there are many reasons why the amplitude in the EMG signal and the force produced by the muscle may not correlate directly, including cross-talk, location of the recording electrodes and the involvement of synergistic muscles in force generation (Kuriki et al., 2012).

Today, amplitude is derived from the time domain and from the band-passed EMG signal, often expressed as a mean absolute value (MAV), also called the average rectified value (ARV) or RMS (Cifrek, Medved, Tonkovic, & Ostojic, 2009; Kamen & Gabriel, 2010b). The ARV amplitude is expressed in mV or µV and is calculated from the absolute value of each datum of EMG over a specific time interval (0,*T)* providing the absolute value of a datum of EMG in that data window (Kamen & Gabriel, 2010b). The RMS amplitude is obtained from a nonlinear detector based on the square law, which does not require rectification (Kamen & Gabriel, 2010b).

According to Clancy, Morin, and Merletti (2002) the amplitude can be estimated from a cascade processed in five stages: (1) noise rejection/filtering, (2) whitening, (3) demodulation, (4) smoothing and (5) relinearization. In voluntary contractions, measuring changes in muscle activity RMS may be a more meaningful amplitude parameter since it represents the power of the signal and has both physical and physiological meaning (De Luca, 1997; Kamen & Gabriel, 2010b). The ARV, on the other hand, represents the area under the signal and does not have a specific physical meaning (De Luca, 1997). The ARV is also affected by cancellation (De Luca, 1979; De Luca & van Dyk, 1975).

2.4.3.4 Integrated electromyography (iEMG)

Integrated EMG (iEMG) quantifies the amount of muscle activity within a set time period and has been used for quantitative EMG relationships, e.g. EMG vs. force or EMG vs. work. It is considered the best measurement for total muscular effort. It can be computed in different ways, for example by a mathematical integration of the area under the absolute values of EMG time series, RMS or electronically. When calculated electronically it always requires full-wave rectification and includes the unfiltered raw EMG signal. Therefore it is especially important to first inspect the raw EMG signal and remove potential DC-offsets and other noise. Integrated EMG can be computed using various methods, for example by a simple time integration, integration and reset after a fixed time interval, integration and reset after a particular value has been determined from the area underneath the rectified EMG signal. For cyclic movements this is most often calculated for each cycle or for each phase duration within the cycle. The measurement unit for iEMG is µV.s.

2.4.3.5 Spectral analysis

While amplitude and timing analysis are performed on the original signal in the time domain, spectral analysis looks at the frequency domain of the EMG signal. Spectral analysis is most often used to assess onset of muscular fatigue. During sustained contractions, the signal spectrum is compressed towards lower frequencies (Cifrek et al., 2009).

Through Fourier Transform any signal can mathematically be transformed into sine waves of different frequencies, to distinguish the contribution that each frequency makes to the original signal. The signal should be stationary in order to obtain meaningful information from this calculation (Zazula, Karlsson, & Doncarli, 2004). Therefore, isometric contractions are often used. Power Spectral Density (PSD) is then used to present the power that each frequency contributes to the EMG signal and is calculated by squaring the Fourier Transforms from each data segment and then averaging them. Spectral analysis can then be used to study how these frequency components change over time. Qualitative (comparing PSDs for each data segment) and quantitative (mean and median frequency) assessments can be made. When fatigue sets in, there is a shift towards lower frequencies. Mean frequency is considered less variable than median frequency.

2.4.4 Muscle coordination and activation patterns with electromyography

Muscle coordination is defined as “a distribution of muscle activation or force among individual muscles to produce a given combination of joint movements” (Prilutsky, 2000). Muscle coordination is often reported through the muscle activation or EMG patterns of muscles contributing to the movement (Billaut, 2011). Today there are still uncertainties regarding whether muscle coordination in dynamic contractions can be precisely studied using EMG. One basic challenge is to understand the coordination between muscles due to muscle redundancy when performing motor tasks (Ting & McKay, 2007).

2.4.4.1 Normalization of the time

In order to create a muscle activation profile based on several cycles, a time normalization must be applied to the linear envelope (Hug, 2011). This is to deal with the fact that consecutive cycles or different phases within a cycle have different lengths in real time. Therefore, start and end points for each cycle or cycle phase must be identified from a mechanical event or a distinct position in the movement pattern and then interpolated. Then the linear envelopes over a number of consecutive cycles are averaged to form an ensemble-averaged EMG as a representative EMG profile for each muscle (Clarys & Rouard, 2011; Hug & Dorel, 2009; Kleissen, 1990; Shiavi et al., 1998). This is usually applied to EMG signals associated with cyclical activities and greatly facilitates comparisons between participants and between experimental conditions.

The number of cycles needed to form a representative muscle profile is uncertain. According to Arsenault, Winter, Marteniuk and Hayes (1986) three strides during gait measurement were sufficient. Shiavi et al. (1998) found that 6-10 strides were sufficient in order to produce a representative pattern, depending on the variability in the muscle, while 20-40 cycles were recommended in other studies (Hug, Turpin, Guevel, & Dorel, 2010; Kadaba, Wootten, Gainey, & Cochran, 1985; Murray, Mollinger, Gardner, & Sepic, 1984). During short-course swimming it might take a swimmer 6-12 SC to complete a length. Therefore, in order to obtain a sufficient number of SCs to report a representative muscle activation pattern in swimming, the reproducibility of SCs should be investigated.

2.4.4.2 Normalization of the amplitude

A normalization of the EMG amplitude is necessary to compare measurements on different occasions, between muscles, in different recording sessions and between individuals (Burden, 2010; De Luca, 1997; Halaki & Ginn, 2012). According to Lin et al. (2008), EMG normalization is frequently used to improve reliability by decreasing variation within and between individuals. This is due to the many technical, physiological and anatomical factors that can influence the EMG magnitude (De Luca, 1997; Knutson, Soderberg, Ballantyne, & Clarke, 1994; Lehman & McGill, 1999).

Normalization is often performed with respect to a reference EMG value. This is obtained from the same muscle, the same electrode configuration, the same factors that affect the EMG signal during the task, and with the same reference contraction (Halaki & Ginn, 2012) from each participant. This is performed by dividing the EMG obtained in a specific task by the EMG from a reference contraction of the same muscle (Burden, 2010). The magnitude of the EMG from the investigated task is then expressed as a proportion of the reference EMG, most commonly as a percentage (Clarys, 2000; Clarys & Cabri, 1993; Cram & Kasman, 1998).

Today a variety of methods are applied to normalize the EMG amplitude, including: peak amplitude during an isometric maximal voluntary contraction (iMVC); peak or mean amplitude from the activity under investigation; peak EMG from submaximal isometric and non-isometric contractions; peak to peak amplitude of the maximum M-wave (M-max); arbitrary and specific angle isometric voluntary contractions; and angle and angular velocity-specific maximal isokinetic voluntary contractions (Burden, 2010; Halaki & Ginn, 2012).

One of the most frequently employed normalization procedures is to compare the myoelectric activity of a given contraction to the activity of an iMVC (Burden, 2010; Halaki & Ginn, 2012; Knight, Martin, & Londerdee, 1979; Woods & Bigland-Ritchie, 1983). However, there are some debates about whether a dynamic movement like swimming can use iMVC for normalization. Studies conducted by Clarys (1983) and Lewillie (1973) found dynamic percentages to be more than 150% of the iMVC during swimming. Another method is therefore to normalize the EMG from a peak or mean EMG of the task under investigation, which can facilitate reduction of inter-individual variability (Burden, 2010).

Challenges in inter-subject variability can be due to differences in motor control, EMG technique, methods for data processing, crosstalk (picking up signals originating from nearby muscles), spatial variability of electrode location, and cut-off frequency used for smoothing the linear envelope (Hug, 2011). Therefore, Hug (2011) claims that the “main drawback of the studies in muscle coordination is the lack of precise information about the degree of muscle activity level, which is related to the lack of an accurate normalization method.” Neither iMVC nor dynamic EMG is guaranteed to reveal how active a muscle is in relation to its true maximal activation capacity (Burden, 2010).

2.4.5 Timing analysis

In addition to analyzing the peak timing and magnitude of the muscle activation profiles, timing analysis can be used to determine the onset and offset of muscular activity. Key factors in determining onset and offset are: the EMG signal originates from the muscle of interest (crosstalk from nearby muscles), and the signal amplitude surpasses the noise amplitude in the detection and recording equipment (De Luca, 1997). Crosstalk is a major challenge in determining onset and offset due to the amplitude of the signal being low and near the noise level. De Luca and Merletti (1988) found as much as 17% of electrical activity on the surface of the muscle of interest was actually recorded from nearby muscles in the leg.

A common approach is to calculate the maximum EMG value that the muscle burst reaches and then consider the muscle active when it surpasses a predetermined percentage of that maximum value. For example, Li and Caldwell (1998) used 25% as their threshold value, Hull and Hawkins (1990) used a threshold of 30%, while Hug (2011) found this threshold level to usually be fixed between 15-25% of the peak EMG. Özgünen, Çelik, and Kurdak (2010) reported that using a single threshold value for different exercise intensities might cause misleading results.

Another common approach is to measure a resting EMG and then consider a muscle active when the activation level increases beyond several standard deviations (SD) from the baseline for a specific time period. This method is also highly subjective since the researcher must choose an arbitrary value for both activation and the time length for considering the muscle active. For instance, Karst and Hasan (1991) used a threshold of 10 SD above baseline for 7.5 ms, while Raasch, Zajac, Ma and Levine (1997) used 3 SD for 55 ms. Hug (2011) identified a standard deviation of 1, 2, or 3 beyond the mean baseline activity to be the most common.

More sophisticated methods have been used, such as wavelet transform (Merlo, Farina, & Merletti, 2003) and the consideration of dynamic parameter profiles (Staude & Wolf, 1999). The most thoroughly tested and validated computer algorithm is the double threshold method (Kamen & Gabriel, 2010b). Briefly, the first criterion for onset detection in the linear envelope is that the amplitude must surpass an amplitude threshold. The second criterion is that this amplitude must stay above the threshold for a certain amount of time. When analyzing groups of muscles this method provides a tool for establishing a muscle activation timing pattern in dynamic movements. This provides valuable information in order to identify how muscles are recruited and controlled in specific movements and to identify optimal movement patterns.

2.4.5.1 Muscle coactivation

Muscle coactivation, as defined by Psek and Cafarelli (1993) is the result of simultaneous activation in agonist and antagonist muscles around a joint during voluntary contractions. The agonist muscle produces movement of the joint while the antagonist muscle opposes it (Yamazaki, Suzuki, Ohkuwa,

& Itoh, 2003). Coactivation between muscles is generally involved in these processes to determine movement efficiency, safety, control over the precision and velocity of the movement, and to stabilize a single joint (Basmajian & De Luca, 1985; Frost et al., 1997; Neumann, 2010). The coactivation between quadriceps and hamstrings is important for knee joint stabilization during many athletic activities (Kellis, 1998; Solomonow et al., 1987) as well as joint stability from coactivation in the ankle joint during locomotion on land (Ratel, Duché, & Williams, 2009). Coactivation also tends to increase with degree of load instability (De Serres & Milner, 1991; Franklin, So, Kawato, & Milner, 2004; Milner, 2002); for example, wrist muscles show more coactivation against an unstable load compared with a constant or elastic load. On the other hand it is unclear whether or not movement velocity influences coactivation (Lauer, Figueiredo, Vilas-Boas, Fernandes, & Rouard, 2013).

It is often assumed that the central nervous system (CNS) controls movements so that energetic cost is minimized and muscle activity is one of several variables (Huang et al., 2012). However, older adults show a higher coactivation and metabolic cost than young adults during walking, which can be linked to safety and increased joint stability to prevent falling during descending gaits (Hortobágyi et al., 2011). A decrease in muscle coactivation and stiffness have also been related to forming and updating the internal model during motor learning of a novel arm-reaching task (Thoroughman & Shadmehr, 1999). While coactivation is necessary during certain movements (Draganich et al., 1989) excessive activation in agonist and antagonist muscles is associated with increased metabolic cost and a "waste" of energy (Frost et al., 2002; Hortobágyi et al., 2011; Huang et al., 2012; Ratel et al., 2009), which could lead to earlier onset of fatigue during competitions and therefore be detrimental to performance.

Today a variety of indices are used to calculate and express coactivation in dynamic movements. It can be expressed from different mathematical calculations in a co-contraction or coactivation index (CI). Coactivation was expressed as the duration of a movement or a movement phase in some studies (Frost et al., 1997; Lamontagne, Richards, & Malouin, 2000), where the duration of agonist–antagonist coactivation (over a threshold) was divided by the duration of the cycle or phase.

Coactivation can also be calculated as an index from the iEMG (Lauer et al., 2013) where $iEMG_{anta}$ and $iEMG_{ago}$ respectively refer to the iEMG of antagonist and agonist muscles in a given phase. Ervilha, Graven-Nielsen, and Duarte (2012) tested two of the most common indices derived from the amplitude of the EMG signal: 1) antagonist muscle activity (the muscle with the lowest muscle activation) divided by the mean of agonist and antagonist muscle activity; and 2) the ratio between antagonist and agonist muscle activation.

2.4.6 Conducting electromyography in the water

There are notable challenges in conducting EMG in the water including waterproofing the electrodes and the system in order to avoid water infiltration, and adhering the electrodes to the skin for a prolonged period of time. Therefore, it is common to cover the electrodes with a water-resistant adhesive film (Benfield, Newton, & Hortobágyi, 2007; Caty et al., 2007; Chevutschi, Lensel, Vaast, & Thevenon, 2007; Rouard & Clarys, 1995). Some previous studies have measured the reliability of iMVC comparing land and water EMG. These studies found conflicting results regarding whether EMG amplitude is similar for the two conditions (Table 2). From these studies Veneziano et al. (2006) identified three residual factors that could influence EMG recordings in water: 1) the buoyancy effect in water can reduce the actual force produced compared to measuring in air; 2) differences between water and air temperature can further increase heat transfer in water; and 3) waterproofing electrodes with adhesive protection needs to be applied to land-based testing as well since the adhesive protection can introduce differences in electrode pressure on the skin. By eliminating these factors they found no changes in the average RMS and median frequency values between measurements taken underwater and in air.

Table 2

Reliability studies with electromyographic measurements on land and in water

Authors	Year	ABP	BB	BF	GAS	RF	TA	TB	VL	VM
Abbiss et al.	(2006)								X	
Alberton et al.	(2008)								X	
Carvalho et al.	(2010)		X							
Clarys et al.	(1985)		O							
Kalpakcioglu et al.	(2009)		O							
Pinto et al.	(2010)		X	X		X		X		
Pöyhönen et al.	(1999)			O					O	O
Rainoldi et al.	(2004)		X							
Silvers & Dolny	(2011)			X	X	X	X			X
Veneziano et al.	(2006)	X								

ABP = abductor pollicis brevis, BB = biceps brachial, BF = biceps femoris, GAS = gastrocnemius medialis, RF = rectus femoris, TA = tibialis anterior, TB = triceps brachial, VL = vastus lateralis, and VM = vastus medialis.
(X) = Good reliability between land and water surface electromyographic measurements.
(O) = Lower amplitude measurements in water than on land.

2.4.7 Electromyographic measurements in swimming

With EMG recordings, it is possible to observe an expression of the dynamic involvement of specific muscles in the propulsion of the body through the water (Clarys, 1985) and to describe swimming technique through muscle participation, synchronization and intensity (Clarys & Rouard, 2010).

Knowledge gained from EMG measurements contributes to a better understanding of coordination, coactivation and intensity of activity in muscles and their relative contribution to overall propulsion. This in turn can help coaches and athletes to better plan training interventions, to focus on a particular phase in the motion, train specific muscle groups and use specific equipment to improve technique (Clarys & Cabri, 1993; Hug & Dorel, 2009).

Ikai, Ishii, and Miyashita (1964) were the first researchers who successfully recorded muscle activation patterns underwater with EMG signals during human swimming. Lewillie (1967) and Lewillie (1968) introduced techniques using telemetry EMG measurements. These were later improved by Piette et al. (1979) and Clarys et al. (1983). Measuring swimming technique through the use of EMG today is primarily conducted using either conventional online registrations or telemetric systems/devices (Clarys & Rouard, 2011).

A literature review conducted by Martens et al. (2015) prior to August 2013 revealed 47 publications in English regarding humans swimming in water using competitive swimming strokes and EMG, excluding fatigue studies, injuries or impairment, and master's or Ph.D. theses. The vast majority of these articles were conducted prior to the 1990s and mostly dealt with front crawl. An overview of studies identified and their main findings with regard to breaststroke swimming is presented in Table 3.

Table 3

Overview of publications with electromyography (EMG) in breaststroke swimming

Author (yr.)	Purpose of the study	Participants	Main findings	EMG type	Muscles studied
Ikai et al. (1964)	Arrange equipment for recording EMG in swimming. Compare high level versus lower level swimmers.	Males 9 Olympic participants 5 students from University swim club	Chronological order of participation and patterns of muscular activity. Muscle activation patterns from Olympic swimmers were more effective.	Surface on-line	FCU, ECU, BB, TB, D, PM, Tmaj, T, LD, RA, GM, RF, BF, TA
Delhez et al. (1971)	Describe EMG of diaphragm during swimming	1 Swimming champion 1 Experienced swimmer	At lesser speeds, respiratory rate was 30% higher in experienced vs champion swimmers.	Esophageal wired surface with memory	Diaphragm
Lewillie, (1971)	Describe differences in 4 swimming styles linked to path of hand and foot.	(not given)	TB activation short and intense.	Surface telemetric	TB, Quadriceps
Lewillie (1973)	Describe EMG at slow, normal and sprint speed.	1 Swimmer of national class	Improved performance at normal speed is from an effective increase of the duration of the leg thrust, while at sprint it is from an increase in the arm pull and shortening of the interval	Surface telemetric	TB, RF
Lewillie (1974)	Superimpose EMG on kinematics of elbow joint	(not given) swimmers not of international caliber	No relationship between the speed of flexion-extension of the elbow joint and the level of EMG activity from BB and TB.	Surface telemetric	BB, TB
Maes et al. (1975)	Compare normal swimmers and water polo players	13 Male all-around swimmers and water polo players (mean age 21 yrs.)	Characteristics of the muscles were found with BF and TA being important.	Surface telemetric	BB, FCU, RA (below and above umbilicus), BF, TA

Table 3. *continued*

Author (yr.)	Purpose of the study	Participants	Main findings	EMG type	Muscles studied
Tokuyama et al. (1976)	Examine characteristics of swimming from infants to adults	37 from 10-month-old infant to unskilled and skilled adults	Recognized differences in the knee and hip movements between skilled adults and unskilled children during the arm pull and kick phase	Surface on-line	TA, G, VM, RF, BF, GM, RA, S, BB long head, TB lateral head, DA, DP, PM "sterno portion", LD
Yoshizawa et al., (1976)	A more detailed analysis of EMG and kinematics during full, moderate and slow speed.	21 from 3 categories: Olympians, University swim club, average adults	Olympians swam most effectively. Found EMG patterns for the kick, arm pull glide and recovery phase.	Surface on-line	TA, G, VM, RF, BF, GM, RA, S, BB long head, TB lateral head, DA, DP, PM "sterno portion", LD
Yoshizawa et al. (1978)	Compare continuous and glide stroke in the functional mechanism of the muscles and the reflex movements of the hip and shoulder joints.	4 Olympic swimmers Male and female	Described muscle activation patterns for both styles and identified distinct similarities and differences between them.	Surface on-line	TA, G, VM, RF, BF, GM, RA, S, BB long head, TB lateral head, DA, DP, PM "sterno portion", LD, FCR, ECRB
Dupuis et al. (1979)	Examine muscular forces of the hand with respect to kinematics of swimming at moderate and sprint paces	3 Female intercollegiate swimmers	DP, wrist flexors and TB active in backward-downward-outward phase. DA and wrist flexors active during backward-downward-inward phase. Nothing reported with regard to swim pace.	Surface on-line	DA, DP, TB, Wrist flexors
Yoshizawa et al. (1983)	Effect of EMG-biofeedback training on swimming	3 Top level Japanese swimmers (participated in World Championships and Olympics)	About 30 min of training to obtain sustained discharge patterns in FCR and D, but long time to establish a fixed pattern. Speed improved after 1 to 3 months.	Surface telemetric	D "pars spinata", PM "pars abdominalis", LD, FCR
Nuber et al. (1986)	Describe muscle activity of shoulder muscles.	10 Male and 1 female 7 university/master 2 past competitive 2 amateurs 19-35 yrs.	No attempt to quantify EMG activities for swimming. Muscular activity was found and presented during recovery and pull-through phase. BB firing was inconsistent.	Fine wire on-line	BB, SSC, LD, PM clavicular head, SSP, ISP, SA, D "middle part"

Table 3. *continued*

Author (yr.)	Purpose of the study	Participants	Main findings	EMG type	Muscles studied
Ruwe et al. (1994)	Compare muscle activity in 12 shoulder muscles between swimmers with and without shoulder pain	25 Normal (20-67 yrs.) 14 painful (19-48 yrs.) Collegiate/master competitive swimmers	The first article to create a reference base for the muscle activation patterns of the upper limbs	Fine wire telemetric	DA, DM, DP, SA, T upper part, RM, SSC, SSP, ISP, Tmin, LD, PM
Daniel & Klauck (1999)	Compare force and speed parameters of the arm pull to muscle coordination during free and fully tethered swimming and arm pulling on land	1 Male Competitive swimmer 27 yrs.	Muscle coordination was similar between free and fully tethered swimming and corresponded to arm pulling on land under the conditions of the land training devices.	(not given)	PM, D, TB, Tmaj
Olstad et al. (2014)	*Muscle activation during normal swimming (60% and 100% effort) compared to one technique exercise at 100% effort*	*1 Male world champion* *26 yrs.*	*iEMG was higher during normal swimming than the technique exercise.*	*Surface telemetric*	*BF, RF, G, TA*
Guignard et al. (2015a)	*Investigate EMG profiles characterizing lower limb flexion-extension*	*3 Females* *1 international level* *2 Female national level* *Mean age 19.7 yrs*	*Strong between-subject variability in muscular activities.* *Only international swimmer maintained G activity during gliding.*	*Surface telemetric*	*BF, RF, G, TA*

Yr = year, Yrs = years, iEMG = integrated electromyography, D = deltoideus, DA = deltoideus anterior, DM = deltoideus medialis, DP = deltoideus posterior, SA = serratus anterior, T = trapezius, RM = rhomboids, SSC = subscapularis, SSP = supraspinatus, ISP = infraspinatus, Tmaj = teres major, Tmin = teres minor, LD = latissimus dorsi, PM = pectoralis major, BB = biceps brachii, TB = triceps brachii, FCU = flexor carpi ulnaris, ECU = extensor carpi ulnaris, G = gastrocnemius, RA = rectus abdominis, GM = gluteus maximus, TA = tibialis anterior, VM = vastus medialis, BF = biceps femoris, ECRB = extensor carpi radialis brevis, S = sacrospinalis, RM = rhomboid major, and RF = rectus femoris.

Studies mentioned in italics are results from our research group.

3. Aims and hypotheses of the thesis

Referring to the rationale for this thesis and the preceding theoretical framework, the main aims of this Ph.D. were to investigate the reliability of conducting prolonged EMG measurements in water, develop a specific method for phase division for the contemporary breaststroke leg kick that would encompass different techniques and coordination styles used by elite swimmers, investigate whether there are changes in the muscular activation pattern and amplitude with increasing effort in elite breaststroke swimmers, and identify performance discriminators from a neuromuscular perspective in world champions (WC+), world-class (WC) and national elite (NE) breaststroke swimmers performing at maximal effort. The aims and hypotheses were to:

Study 1:

- compare surface electromyographic measurements from iMVCs on dry land and in water from muscles that are of high relevance to breaststroke technique. We hypothesized that the EMG amplitude would be the same before and after 90 min of submersion (including 60 min of easy swimming) using minimal measures for waterproofing the electrodes, and between land and water measurements.

Study 2:

- develop a specific method for identifying and measuring the phases during the contemporary breaststroke leg kick in elite swimmers, allowing a phase division that encompasses the different techniques and coordination styles, using 3D motion-capture with automatic motion tracking.

Study 3:

- investigate the relationships between muscle activation in eight different muscles and kinematic variables during three different effort levels (60-80-100%) in elite breaststroke swimmers. We hypothesized that muscular activation would increase with increasing effort while the timing of muscle activation onset/offset would remain similar.

Study 4:

- characterize the lower limb flexion-extension movements during the breaststroke kick performed by high-level swimmers from muscular and kinematic points of view.

Study 5:

- investigate potential differences in muscle activation and coordination between WC+, WC and NE breaststroke swimmers for the SC and phases during maximal effort. We hypothesized that WC+ and WC swimmers would show a different and more economical muscle activation pattern than NE swimmers.

4. Methods

4.1 Participants

In total, twenty-one participants (twelve students and nine elite swimmers) volunteered (with some of the swimmers participating in several studies). The characteristics of the participants are summarized in Table 4. *Study 1* included 12 healthy, well-trained students with good swimming skills. *Study 2* included three WC swimmers. *Studies 3-5* included both WC and NE swimmers. World-class breaststrokers were classified as medalists at international championships within the past two years (including two world champions (WC+)). National elite breaststrokers were classified as medalists at the Norwegian national championships.

Table 4

Participant characteristics across studies (mean ± SD)

Study	n	Sex	Age (yrs.)	Body weight (kg)	Height (cm)	Reaching height (cm)	FINA-points	FINA-points range
1	6	Female Students	23.3 ± 2.6	61.6 ± 8.3	168.5 ± 6.0			
	6	Male Students	23.3 ± 2.0	82.2 ± 7.4	185.0 ± 5.8			
2	1	Female WC	28.3	73.3	168.0	214.0	994.0	
	2	Male WC+	27.3 ± 1.7	86.6 ± 0.8	188.0 ± 2.8	243.3 ± 1.1	1009.0 ± 22.6	994-1025
3	5	Female Elite	20.3 ± 5.4	64.3 ± 5.4	168.5 ± 3.7	214.4 ± 6.3	815.4 ± 160.4	654-994
	4	Male Elite	27.7 ± 7.1	84.8 ± 2.2	186.5 ± 2.9	239.5 ± 5.1	879.0 ± 150.7	746-1025
4	1	Female WC	28.3	73.3	168.0	214.0	994.0	
	2	Female NE	16.0 ± 1.9	63.9 ± 0.2	168.3 ± 6.0	210.5 ± 3.5	674.5 ± 29.0	654-695
5	2	Female WC	25.5 ± 4.0	66.2 ± 10.1	167.0 ± 1.4	213.0 ± 1.4	986.5 ± 10.6	979-994
	2	Male WC+	27.3 ± 1.7	86.6 ± 0.8	188.0 ± 2.8	243.3 ± 1.1	1009.0 ± 22.6	994-1025
	2	Female NE	16.0 ± 1.9	63.9 ± 0.2	168.3 ± 6.0	210.5 ± 3.5	674.5 ± 29.0	654-695
	2	Male NE	28.0 ± 12.1	83.1 ± 1.3	185.0 ± 2.8	235.8 ± 4.6	749.0 ± 4.2	746-752

WC = world-class swimmers, NE = national elite swimmers, and WC+ = world champions.

4.2 Ethical considerations

The studies were approved by the external and internal scientific committees assigned by the Norwegian School of Sport Sciences. The protocols were approved by the Regional Committees for Medical and Health Research Ethics of Southern Norway (REK) (reference number: 2010/2893a) (appendix A) and were in accordance with the Declaration of Helsinki. Thereafter, the project was submitted to and approved by the Norwegian Social Science Data Services (NSD) (reference number: 25476) (appendix B). All participants older than 18 years of age signed a voluntary informed consent, and the legal guardians of all participants younger than 18 years of age gave their written informed consent on behalf of the children prior to the studies (appendix C).

The ethical dilemmas of conducting experiments with top level athletes underwent a thorough analysis during the writing of an essay in the philosophy of science, "Etiske utfordringer ved anonymitet og forskning på toppidrettsutøvere", translated to "Ethical considerations concerning anonymity and research on top level athletes."

4.3 Experimental approach

4.3.1 Familiarization

For *Study 1* all participants completed a familiarization session 5.0 ± 1.1 days before the main testing. The familiarization session included skin preparation, marking of the electrode sites on the body and on transparent plastic covers and performance of three iMVC's on land, with instructions for all eight exercises. For *Studies 3-5*, the swimmers first executed the exercises on land with minimal force to acquaint themselves with the testing conditions and to ensure correct execution of the movement. Before testing in the water the participants in *Studies 2-5* moved around in the water to become familiarized with the equipment before conducting their swimming warm-up with all the equipment for further familiarization.

4.3.2 Study design

All measurements were performed on the pool-deck and/or in one 12.5 m and/or one 25 m indoor swimming pool at the Norwegian School of Sport Sciences, with air and water temperatures of approximately 29 °C. *Study 1* was conducted to establish a reliable methodology for conducting EMG in water, which was later used throughout *Studies 3-5*. *Study 2* was conducted to establish a specific method for identifying the phases of the contemporary breaststroke leg kick in elite swimmers and was adapted throughout *Studies 3-5*.

For *Studies 3-5*, the participants were first prepared with the EMG equipment before iMVCs were performed on the pool-deck for each muscle using the methods reported in *Study 1*. Thereafter, in *Studies 2-5* they were prepared with the equipment necessary for conducting the 3D kinematic analysis with automatic motion tracking, before entering the water for a personalized swimming warm-up with all of the equipment (Figure 5). The warm-up consisted of 15 min of low- to moderate-intensity aerobic swimming with elements of kicking and drill exercises.

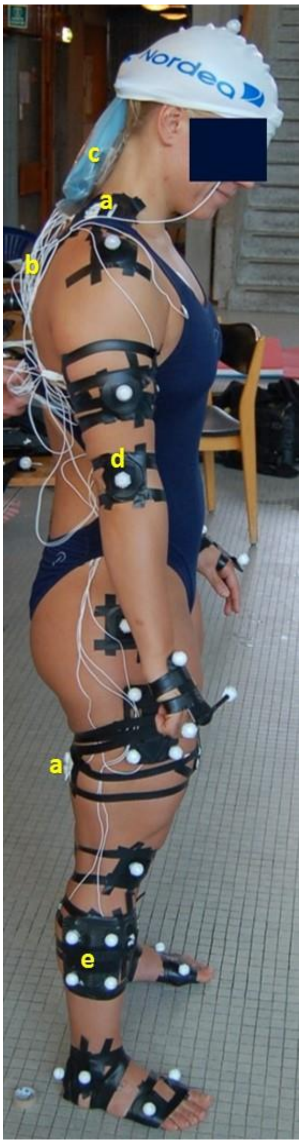

Figure 5. A swimmer being prepared with the testing equipment.
(a) Electromyographic (EMG) electrodes; (b) cables coming from the EMG sensors to the input box; (c) the waterproof pouch containing the input box with Bluetooth transmitter and data logger; (d) 3D marker on silicone thread for fastening to the body with insulating tape around the perimeter; and (e) 3D four marker cluster.

4.3.2.1 Reproducibility of electromyographic measurements (Study 1)

To investigate the reliability of EMG measurements after a prolonged submersion for 90 min (including 60 min of easy swimming), twelve healthy, well-trained students with good swimming skills participated (Table 4). Eight muscles on the right side of the body were selected based on conflicting results regarding reliability and lack of reliability studies (Table 2, p. 20), as being involved in breaststroke performance (McLeod, 2010; Ruwe, Pink, Jobe, Perry, & Scovazzo, 1994; Troup, 1999; Yoshizawa, Tokuyama, & Okamoto, 1976). The muscles chosen included some agonist and antagonist muscles and muscles from both limbs. The muscles were: biceps brachii (BB), triceps brachii (TB), trapezius (pars descendens) (TRA), pectoralis major (pars clavicularis) (PM), rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA) and gastrocnemius (medialis) (GAS). A ground electrode was placed on the os frontalis. Isometric MVC testing was used to verify the reliability of the EMG signal on land and under water before and after submersion. For each muscle, the participants were instructed to exert a maximal isometric force performed in standardized exercises (Table 5) and hold it for 5 s, separated by about 45 s of recovery.

Table 5

Description of the exercises used for isometric maximal voluntary contraction testing for each of the eight muscles

Muscle	Procedure
Biceps brachii	Sitting next to a stair. The right elbow was resting on the stair and the right hand grasped a strap. The length of the strap was fixed to reach an elbow angle of 90°, shoulder flexion was 0° and shoulder abduction 30°. The participant pulled the strap towards the chest.
Triceps brachii	Sitting next to a stair. The right hand grasped a strap. The length of the strap was fixed to reach an elbow angle of 90°. Shoulder flexion and abduction was 0°and the participant pressed straight downwards on the strap.
Trapezius (pars descendens)	Standing position. Right shoulder was pressing up against a strap which was fixed underneath the participant's foot and over the right lateral clavicula. Investigators ensured that participants elevated the acromial end of the clavicula and scapula.
Pectoralis major (pars clavicularis)	Standing in front of a ladder. Both underarms touched the ladder with a 90° angle in the elbows and shoulders. The ladder was a little wider than the shoulders and the participants pressed against the ladder.
Rectus femoris	Sitting upright (on a chair) with a strap fixed at the ankle. Participants tried to extend the knee without rotating the thigh while applying pressure against the leg above the ankle in the direction of flexion. The angle of the knee and hip were kept constant at 90°.
Biceps femoris	Lying on a platform in a prone position with a strap fixed at the ankle. The length of the strap was fixed to a knee angle of 135°. The hip angle was 0°. The participant pressed the ankle towards their buttocks.
Tibialis anterior	The first six participants sat on a platform with a 90° angle in the hip and a strap around the bottom of their toes and the ankle at a 90° angle. The participants were instructed to keep the heel on the ground and push their feet towards their ankles. The last six participants supported the leg just above the ankle joint with the ankle joint in dorsiflexion and the foot in inversion without extension of the great toe. Pressure was applied against the medial side, dorsal surface of the foot in the direction of plantar flexion of the ankle joint and eversion of the foot.
Gastrocnemius	The first six participants sat on a stair with a 90° angle in the knee and hip with a strap around the bottom of their ankle at a 90° angle. The participants were instructed to keep their heels on the ground and push their ankle forward. The last six participants had the foot in plantar flexion with an emphasis on pulling the heel upward instead of pushing the forefoot downwards. For maximum pressure in this position it was necessary to apply pressure against the forefoot as well as against the calcaneus.

Each contraction was repeated three times. Strong verbal encouragement was provided during all tests to help participants to perform at maximal effort. Each set of iMVC tests on land and in the water was performed in identical order. During the iMVC testing in water, electrodes were fully submerged. The testing protocol for all participants is described in Figure 6 and an example of iMVC testing of BF on land and in water is presented in Figure 7. Each participant was permitted three trials, with the best result retained for analysis. In order to test the reliability of the equipment after submersion in water, all measurements of variables were performed with the same settings, configurations and personnel during land pre, water pre, water post and land post.

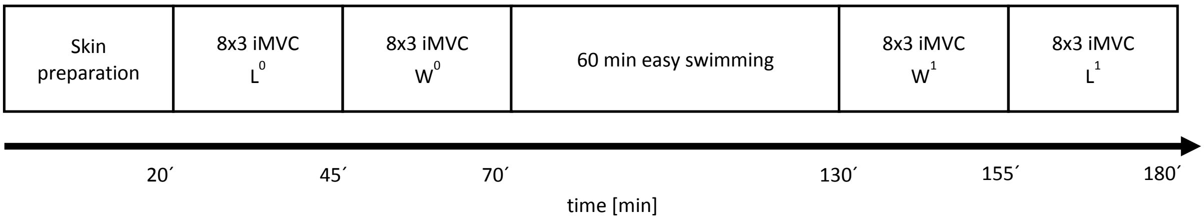

Figure 6. Testing protocol for isometric voluntary contractions.
MVC = isometric maximal voluntary contraction, L° = Land pre, W° = Water pre, W¹ = Water post, and L¹ = Land post.

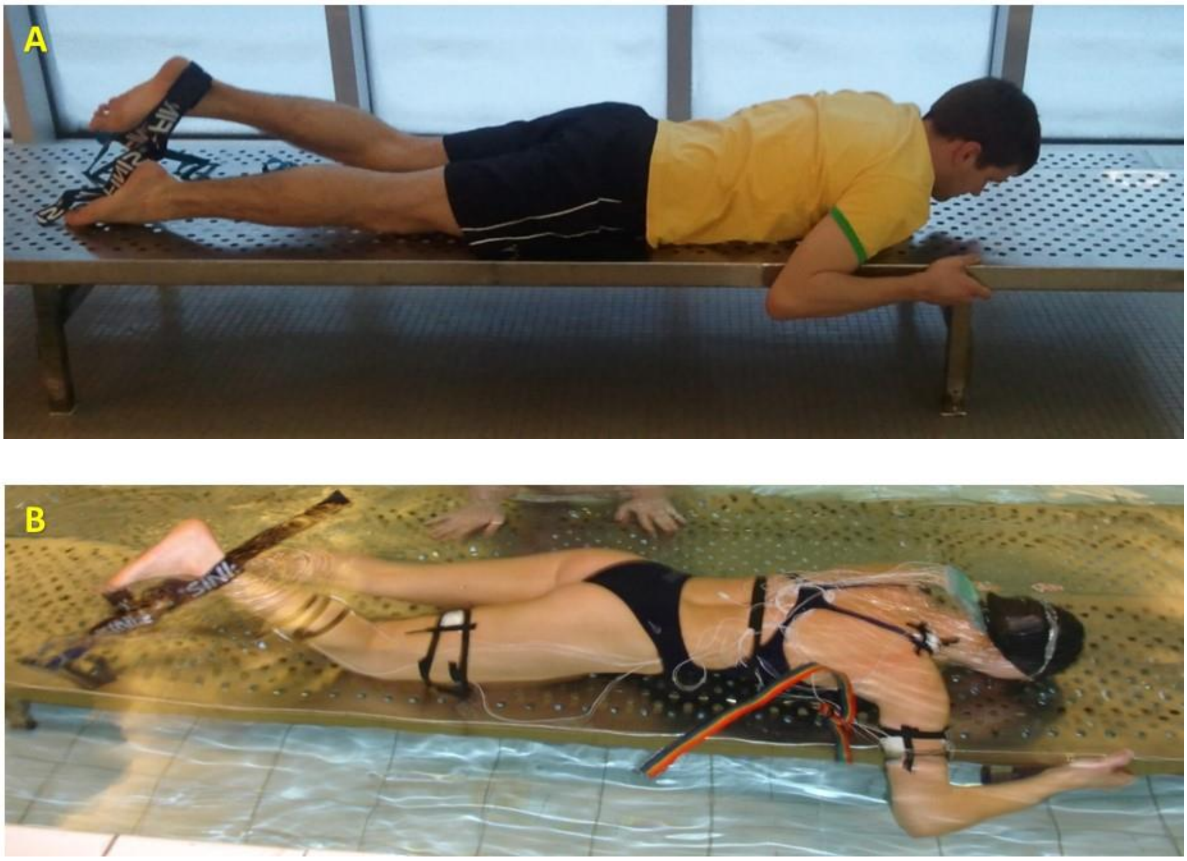

Figure 7. An example of the isometric maximal voluntary contraction exercise used for biceps femoris.
(A) on land; and (B) in water.

4.3.2.2 *Phases of the contemporary breaststroke leg kick (Study 2)*

To investigate a new and specific method for identifying and measuring the phases during the contemporary breaststroke leg kick in elite swimmers, three international medalists participated (world champions and Olympic medalists) (Table 4). The swimmers performed 25 m of breaststroke at 60-70-80-90-100% of maximal effort with 30-45 s of rest in between. Borg's Rate of Perceived Exertion (RPE) was used to verify the effort level (Borg, 1998). Kinematic data was recorded from tracking reflective markers attached to the swimmer's body on the following reference points: iliac crest, 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, and Pensalfini (1997) and de Leva (1996).

4.3.2.3 *Muscle activation and kinematics during submaximal and maximal effort (Study 3)*

To describe muscular activation patterns and kinematic variables during the complete SC and the different phases of breaststroke swimming at submaximal and maximal efforts, nine elite breaststrokers participated (Table 4). The swimmers performed 25 m of breaststroke at 60%, 80% and 100% of maximal effort with 30-45 s of rest in between. Borg's Rate of Perceived Exertion (RPE) was used to verify the effort level (Borg, 1998), where an RPE of 11 corresponded to 60%, an RPE of 15 to 80% and an RPE of 19 to 100% effort. Muscular activity was recorded using EMG from the same muscles as *Study 1*, identified as important for breaststroke performance (Table 3 and Troup, 1999). Kinematic data was recorded in the same manner as for *Study 2*.

4.3.2.4 *Different muscular recruitment strategies among elite breaststrokers (Study 4)*

To consider the possible effect of expertise level on EMG results at maximal effort, three swimmers participated (one WC and two NE) (Table 4). The swimmers performed two 25 m maximal effort breaststroke bouts at a velocity corresponding to their best time for a 100 m race, with 30 s rest in between. The activities of four muscles chosen for their main contribution in the breaststroke flexion-extension (Yoshizawa, Okamoto, Kumamoto, Tokuyama, & Oka, 1978): GAS, TA, RF and BF, were recorded using EMG. The flexion-extension was measured through six reflective markers fixed on the right side of the body: trochanter major, lateral femoral condyle, medial and lateral malleolus, first and fifth metatarsals. Three angles were selected: ankle, from fifth metatarsal, lateral malleolus and lateral femoral condyle markers; knee from lateral malleolus, lateral femoral condyle and trochanter major markers; and thigh from lateral femoral condyle, trochanter major markers and antero-posterior axis.

4.3.2.5 *Muscle activation differences between performance levels (Study 5)*

To study the differences between WC and NE breaststroke swimmers in terms of muscular activation and coordination with support of kinematic variables in a matched controlled group, eight swimmers participated (Table 4). The WC group included two world champions (WC+). The design described for *Study 3* was used.

4.4 Apparatus, materials and procedures

4.4.1 Surface electromyography

In *Studies 1* and *3-5* the procedures for acquiring the EMG signals were performed according to the European recommendations for surface electromyography (SENIAM project) (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000; Hermens et al., 1999) and the International Society of Electrophysiology and Kinesiology (Merletti, 1999; Merletti, Botter, Troiano, Merlo, & Minetto, 2009).

To minimize 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 a diameter of 57 mm, contact surface of 10 mm, inter-electrode distance of 20 mm and with snap connectors of 3.9 mm (Plux Ltda, Lisbon, Portugal) (Figure 8) were positioned at the midpoint of the contracted muscle belly (Clarys & Cabri, 1993). They were placed in line with the direction of the muscle fibers from the anatomical reference points according to the European recommendations for surface electromyography (SENIAM project) (Hermens et al., 2000; Hermens et al., 1999). Two self-adhesive foams (Multi Bio Sensors Inc., 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 silicone covers on the snap created a waterproof seal between the electrode and the participant's skin. This special construction also provided a waterproof seal with the snap connector. The waterproof EMG dipole sensor (Plux Ltda, Lisbon, Portugal) with pre-amplifier (band-pass filter of 25-500 Hz, input impedance > 100 MΩ, common mode rejection ratio was 110 dB and gain of 1000) was embedded in silicone material to provide a waterproof environment and connected to the electrode through the snap (Figure 8).

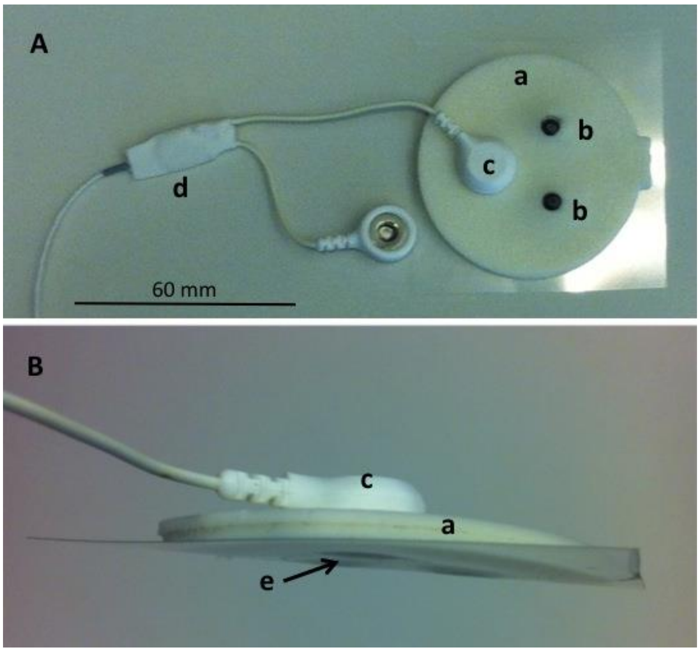

Figure 8. Configuration of the EMG sensors (A) top view; (B) side view.
(a) adhesive electrode holder; (b) sensor connector for clip; (c) connector clip (snap connector); (d) EMG amplifier; and (e) Ag/AgCl pre-gelled sensor (in contact with skin).

The electrode holders were covered with insulating tape around the outside perimeter for protection against water flow and to reduce resistance during swimming. Insulating tape was also used for fixing the cables to the body to limit movement artifacts (Rainoldi, Cescon, Bottin, Casale, & Caruso, 2004). No additional waterproofing of the electrodes, snap connectors or cables was performed (Figure 9).

Figure 9. The electrode, connectors, amplifier, and wires.
(a) input box with Bluetooth transmitter; (b) adhesive electrode holder; (c) snap connector; (d) insulating tape; (e) EMG input channel; and (f) EMG amplifier.

The EMG sensors were connected to the bioPlux Research Input Box (Plux Ltda, Lisbon, Portugal) (Figure 9) with dimensions of 84 · 53 · 18 mm and weight 86 g inside a waterproof pouch (Figure 10) with 8 analogue channels (12 bit), sampled at 1 kHz and with a measuring range of 5 mV.

The cables from the electrodes on the leg were directed along the lateral part of the right leg, through the swimming suit and along the medial back to the waterproof pouch connected to the participant's swim cap (Figure 10). From the upper body the cables were routed to the medial side of the back and into the waterproof pouch.

In *Study 1* the signals were telemetrically recorded through a Bluetooth high range adapter and visually inspected while recording in real time with the MonitorPlux v2.0 software (Plux Ltda, Lisbon, Portugal). In *Studies 3-5* the signals were telemetrically recorded through a data logger placed inside the waterproof pouch during swimming (Figure 10). Before conducting the iMVC's, a resting EMG together with a dynamic contraction was obtained to ensure the quality of the EMG signal. In addition, throughout *Studies 3-5* the quality of EMG was visually assessed in real time, both on land and underwater before the swimming experiments.

Figure 10. The waterproof pouch for electromyographic testing in water.
(a) waterproof pouch; (b) input box; (c) data logger; and (d) cables (coming from the EMG sensors).

4.4.2 3D motion-capture with automatic motion tracking

In *Studies 2-5* a 3D underwater motion capture system (Qualisys, Gothenburg, Sweden) was installed in the pool to record underwater movements at a sampling rate of 100 Hz for kinematic analysis. The system consisted of 10 and 6 Oqus 3 and 5 cameras capturing special retro-reflective markers on the swimmer's body. In the 10 underwater camera set-up, five were placed on each side of the pool, six were mounted just below the water surface and four were standing on tripods underwater (Figure 11). In the 6 underwater camera set-up (due to malfunction, four cameras were removed for the last participants), all cameras were placed on the right side of the swimmer. All cameras were placed inside a waterproof case made of anodized aluminum. Each camera had active filtering hardware, which greatly reduced unwanted reflections from sunlight, bubbles and other particles under water. Each camera was also masked for sunlight reflections. The specialized underwater cameras were connected to a 200 W IP68 power supply placed on land, synchronized, and attached to a PC using Ethernet cabling and a hub. Qualisys Track manager® v2.6 (Qualisys, Gothenburg, Sweden) was used to run the camera setup and capture.

To counter the fact that water absorbs light to a much higher degree than air, the underwater cameras were equipped with a very powerful strobe consisting of 12 high power LEDs with cyan visibility (wavelength 505 nm). The powerful LED system provided good illumination for 12.5 m in clear water and facilitated measurements even with a certain level of particles in the water. Each LED was also equipped with a lens which focused the light to approximately a 40-degree-wide beam. By angling the LEDs individually an even light pattern was produced over the entire field-of-view (FOV) of the cameras.

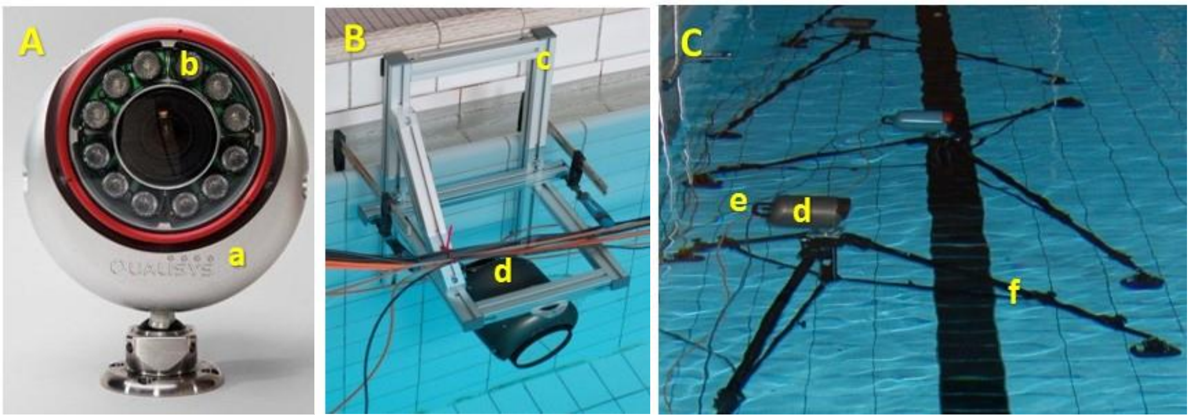

Figure 11. 3D underwater cameras and set-up (A) 3D camera before being placed in underwater housing; (B) 3D camera in underwater housing and mounted to the wall; and (C) 3D cameras standing on tripods in the water. (a) Qualisys Oqus 5 camera; (b) cyan LED; (c) mounting structure on the swimming pool wall; (d) underwater housing in anodized aluminum; (e) robust cables and connectors in IP68 class; and (f) tripods for stability and positioning of the cameras.

4.4.2.1 Calibration

Calibration of the 3D motion capture system was performed with an L-frame reference structure and a moving wand method (Nedergaard et al., 2014) with two markers fixed with an inter-point distance of 749.5 mm following the recommendations of the manufacturer (Qualisys AB, 2011). The wand was manually moved slowly through the calibration volume following the path of the swimmers for 300 s to avoid wobbling of markers due to water resistance. More time was spent in the overlay between two cameras in order to cover as many points as possible; at least 800-1000 per camera. During this process the ‘extended calibration’ option was active because all cameras were not able to view the L-frame, which was placed in the middle of the volume on the bottom of the pool. The cameras were positioned to cover a volume of approximately 37.5 m^3, 10 m (X; horizontally) x 2.5m (Y; width) x 1.5 m (Z; vertically) and the area captured from the cameras is presented in Figure 12. The RMS reconstruction error of the two points on the wand was 1.6 mm.

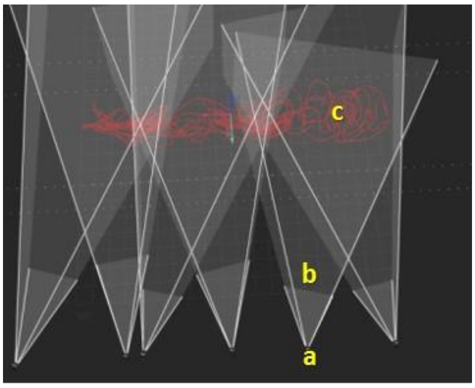

Figure 12. 3D calibrated volume under water.
(a) placement of camera; (b) camera field-of-view (grey); and (c) calibrated volume (red).

4.4.2.2 Markers and reference points on the body

The retro-reflective material used on normal land markers completely loses reflectivity under water. Therefore, markers with special retro-reflective tape developed to suit underwater usage were manufactured by Qualisys (Gothenburg, Sweden). The markers were passive hemispheres with a diameter of 19 mm. All were silicone embedded for fastening and had neutral buoyancy (Figure 13). They were attached to the swimmer’s body on the following reference points: acromion; lateral epicondyle; a three-marker cluster on the hand (one marker at the wrist, and two on the metacarpals); iliac crest; trochanter major; lateral femoral condyle; calcaneus; medial and lateral malleolus; 1st and 5th metatarsals; and two clusters consisting of four markers placed on the midpoint of the vastus lateralis and the peroneus longus (Cappozzo et al., 1997; de Leva, 1996). In addition, four virtual markers (two on the upper arm and the forearm) were created in order to make three independent markers available on these segments (Cappozzo, Della Croce, Leardini, & Chiari, 2005).

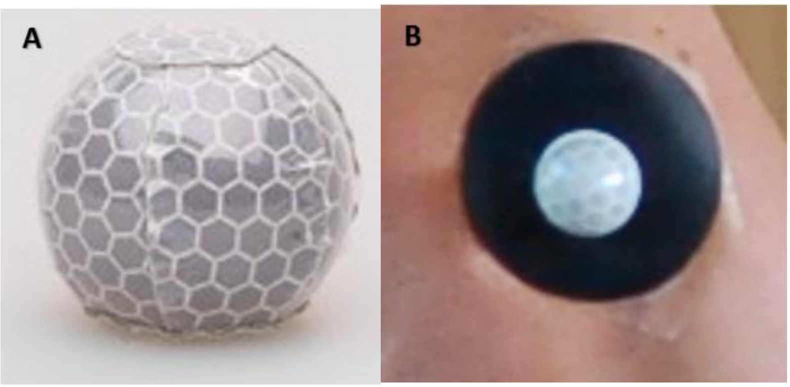

Figure 13. 3D markers and silicone embedding system.
(A) the retro-reflective material covering the marker; and (B) the silicone material embedding the marker for fastening onto the swimmer's body.

4.4.3 Synchronization of the equipment

In *Studies 3-5,* the pool was equipped with four digital underwater cameras, Sony HDR-CX550VE Camcorder (Sony INC, Tokyo, Japan). The cameras were placed inside Sports pack waterproof cases, SPK-HCE (Sony INC, 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 (Figure 14).

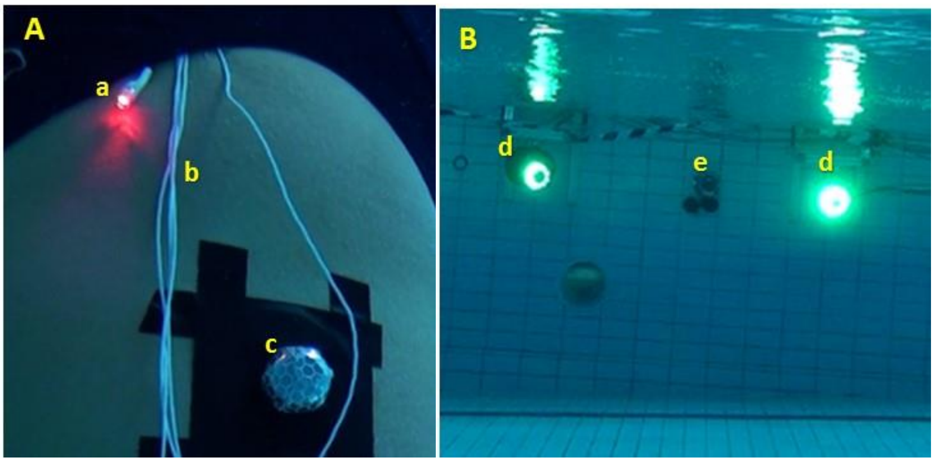

Figure 14. Synchronization of the equipment through the view of the 2D camera (A); and (B).
(a) capturing the first blink of the EMG reference light; (b) cables (coming from the EMG sensors); (c) 3D marker attached to trochanter major with insulating tape; (d) capturing the first blink of the 3D cameras; and (e) one of the 2D cameras placed underwater for verifying the swimming movements in 2D.

4.5 Calculations

4.5.1 Surface electromyography

In *Studies 1* and *3-5* all procedures for processing and analyzing the EMG signals were performed according to the European recommendations for surface electromyography (SENIAM project)

(Hermens et al., 2000; Hermens et al., 1999) and the International Society of Electrophysiology and Kinesiology (Merletti, 1999; Merletti et al., 2009).

In *Study 1*, Python v2.6.7 (Python Software Foundation, Delaware, USA) was used for signal analysis. Raw EMG signals were full-wave rectified and smoothed using a low-pass FIR filter with a cutoff frequency of 500 Hz. The peak EMG amplitude was calculated with 200 ms RMS and the highest amplitude peak for all trials was selected for further analysis (Abbiss, Peiffer, Netto, & Laursen, 2006; Hermens et al., 1999). The power spectrum of the signal (mean average frequency and peak frequency) was analyzed using 2048-point Fast Fourier Transform (FFT).

In *Studies 3 and 5*, the raw EMG signals were visually inspected to ensure quality and 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 (MathWorks, Inc. Natick, MA, USA). The EMG signals were processed as in *Study 3* and smoothed with a low pass filter (12 Hz, 4th order Butterworth). Averaged EMG (avgC) was calculated for each muscle during the SC. In addition, iEMG for each phase and the SC were calculated in *Study 3*. The EMG signals were amplitude-normalized to the individual iMVC. Different SC durations were observed among the swimmers and between the different effort levels. In order to allow a proper comparison between the different efforts levels (*Study 3*) and swimmers (*Study 5*) with respect to muscle coordination, interpolation was performed using MATLAB R2012b (MathWorks, Inc. Natick, MA, USA). In *Studies 3* and *4*, each SC was interpolated to 100 time points (Shiavi & Green, 1983) in order to also identify how the stroke phases shifted with increasing effort. In *Study 5*, each stroke phase was interpolated to 50 time points with respect to the kinematic data in order to account for the intra-individual and inter-individual variability in kinematics (Hug, 2011).

To identify muscular onset and offset in *Studies 3 and 5*, a threshold level of 20-25% of the peak EMG activation during the SC was selected (Hug, 2011). Electromyographic reproducibility was calculated using up to 10 SC at the different effort levels as in *Study 4*. Based on the high reproducibility between the SC, three to five SC at stabilized swimming velocity from the last part of each swim at 60, 80 and 100% effort were selected for further analyses.

In *Study 4*, raw EMG signals were full-wave rectified and smoothed using high- and low-pass filters at 20 Hz and 500 Hz, respectively in MATLAB 2008a (MathWorks Inc., Natick, MA, USA). The signal was normalized towards a dynamic EMG corresponding to the movement (Burden, 2010). For each participant and muscle, the rectified EMG was calculated for the full stroke and partitioned in 50 ms windows to find the $iEMG_{max}$. The rectified EMG was expressed as a percentage of $iEMG_{max}$ among the phases (Burden, 2010). The reproducibility between SCs was calculated for EMG peak value and the time between two consecutive peaks. Based on the high reproducibility between the SC, one SC at stabilized swimming velocity from the last part of the swim was selected for further analyses.

4.5.2 3D kinematic analysis with automatic motion tracking

In *Studies 2-5* Qualisys Track Manager v2.6 and 2.8 (Qualisys, Gothenburg, Sweden) were used to track and process the anatomical markers on the swimmer's body. Swimming velocity, SL, stroke duration, SR and body angles for the complete SC and for each of the phases were measured and calculated from the trajectory of the different markers using a fit to 2nd degree curve filter. For each frame, the filter first finds the 2nd degree curve that best fits the data in the filter window around the current frame. Then the data of the current frame is set to the value of that curve in the current frame.

Based on the four leg kick phases established in *Study 2* (Figure 15), each SC was divided into three phases for *Studies 3-5*: (1) leg kick/propulsion: from the smallest knee angle during recovery until the first peak in knee angle (extension) during the leg kick; (2) gliding: from end of the leg kick to the beginning of active knee flexion for leg recovery; and (3) leg recovery: from end of gliding until the smallest knee angle.

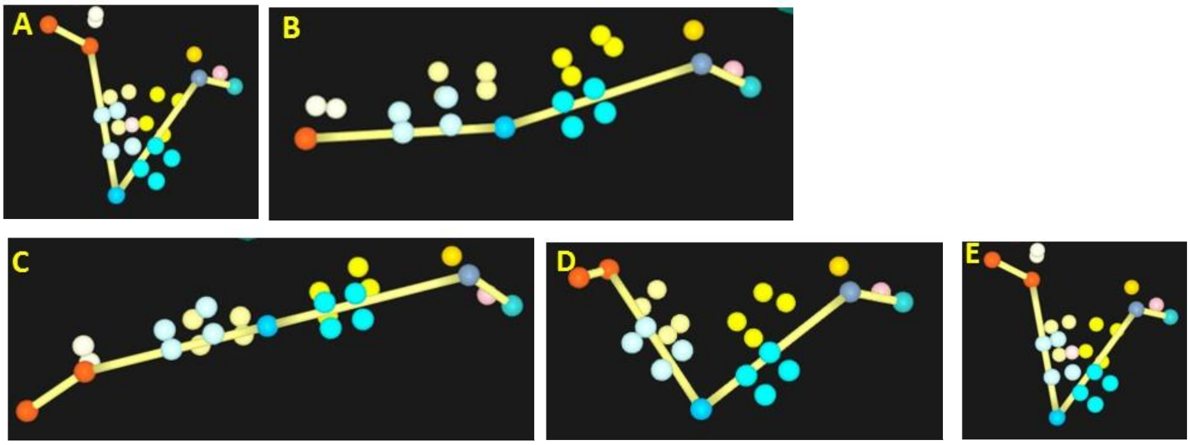

Figure 15. Underwater breaststroke kick with 3D automatic tracking.
(A) beginning of phase 1; (B) beginning of phase 2; (C) beginning of phase 3; (D) beginning of phase 4 (only used in *Study 2*); (E) end of stroke cycle and beginning of phase 1. Color coding of the markers on the bone structure from left to right: ● calcaneus and metatarsals; ● lateral femoral condyle; ● trochanter major; and ● iliac crest.

In *Studies 2-5*, from marker coordinates, the pattern of the knee angle in the sagittal plane was calculated as follows (A represents the marker positioned on the lateral malleolus, K on the lateral femoral condyle and T on the trochanter major) according to equation (1):

$$\widehat{AKT} = \arccos\left(\frac{\overrightarrow{KA} \cdot \overrightarrow{KT}}{\left\|KA \cdot KT\right\|}\right) \quad (1)$$

Similar computations were done for articular ankle and segmental thigh angles in *Study 4*.

4.6 Statistical Analyses

The processed data were transferred to IBM SPSS® Statistics v18.0 and 21.0 (IBM® Corporation, Armonk, NY, USA) and Microsoft Excel 2010 (Microsoft® software, Microsoft Corporation, Redmond, WA, USA) for all further statistical computations.

In *Study 1*, the maximum amplitudes from the three iMVC's for each muscle and each testing condition were used for statistical analysis. A Shapiro-Wilk analysis was used to check for data normality. Repeated measures analyses of variance (general linear model ANOVA) were performed to test overall differences in iMVC peak amplitude between exercise conditions for parametric variables. Friedman's ANOVA was used for variables which were not normally distributed. Typical error, represented by the coefficient of variation (CV%) was calculated to provide an indication of the intra-participant variability between pre and post water submersion for each muscle. Cronbach's test of reliability was carried out on the iMVC signal on land pre and post to evaluate the reproducibility of the iMVC scores. Intraclass correlation coefficients (ICC) (1,1) were calculated for the experimental conditions (land and water, pre and post) within each muscle using a one way random effects model. An ICC greater than 0.80 was considered to represent high reliability (Abbiss et al., 2006; Netto & Burnett, 2006).

In *Studies 3-5*, the reproducibility of the strokes was evaluated for kinematic and muscular parameters. Three lower limb angles (thigh, knee and ankle), the EMG peak value (PV), and the time between two consecutive EMG peaks (TP) from up to 10 SC of the stable portion of the swimming were investigated. The intra-stroke (IS) variability for each participant and muscle was determined with coefficients of variation: PVIS(%) = PVSD/PVmean×100 for EMG and TPIS(%) = TPSD/TPmean×100 for time duration, according to Taylor and Bronks (1995).

In Studies 3 and *5,* 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 *(Study 3)*. Bonferroni post-hoc corrections were carried out to test differences between effort levels.

In Study 5, a one-way ANOVA was performed to test overall differences of the kinematic variables between the SCs and the different stroke phases at 60, 80 and 100% of maximal effort and the level of confidence was set to 95% for statistical differences and 90% for statistical tendencies.

5 Results

The following section briefly summarizes the main findings in *Studies 1-5*. For a more detailed description, the reader is referred to the original papers (included at the end of the thesis).

5.1 Reliability of surface electromyographic measurements on land and in water prior to and after 90 min of submersion (swimming) *(Study 1)*

The EMG recordings and testing procedures showed high reliability and integrity after submersion in water for 90 min. There were no significant differences in peak amplitude iMVC scores between land pre and post measurements for all muscles. General linear model ANOVA showed no difference between EMG conducted on land pre and post for BB, TA, BF and RF, $F(2,19) = 1.03$, $p > .05$ or for land and water pre and post $F(1,12) = 1.38$, $p > .05$. Friedman's ANOVA showed no difference between EMG conducted on land pre and post for TB, TRA, PM and GAS, $x^2(1) = 0.21$, $p > .05$ or for land and water pre and post $x^2(3) = .24$, $p > .05$.

The intraclass correlation coefficient (ICC) between land pre and land post and land pre and water pre showed very strong positive correlations for 15 groups (range .981-.801) and a strong positive correlation for RF land pre & post (.725).

The Cronbach's alpha coefficient was .985 between land pre and land post, .979 between land pre and water pre .979, and .982 between all four conditions.

5.2 Phases of the contemporary breaststroke leg kick *(Study 2)*

The four phases of the breaststroke kick during maximal effort are shown for one swimmer in

Figure *16*. One participant showed a more distinct undulating breaststroke with a much larger knee angle at the beginning and end of phase 1 as well as a smaller knee angle through phase 2 and 3. The slip was similar across the participants, ranging from 300-320 mm.

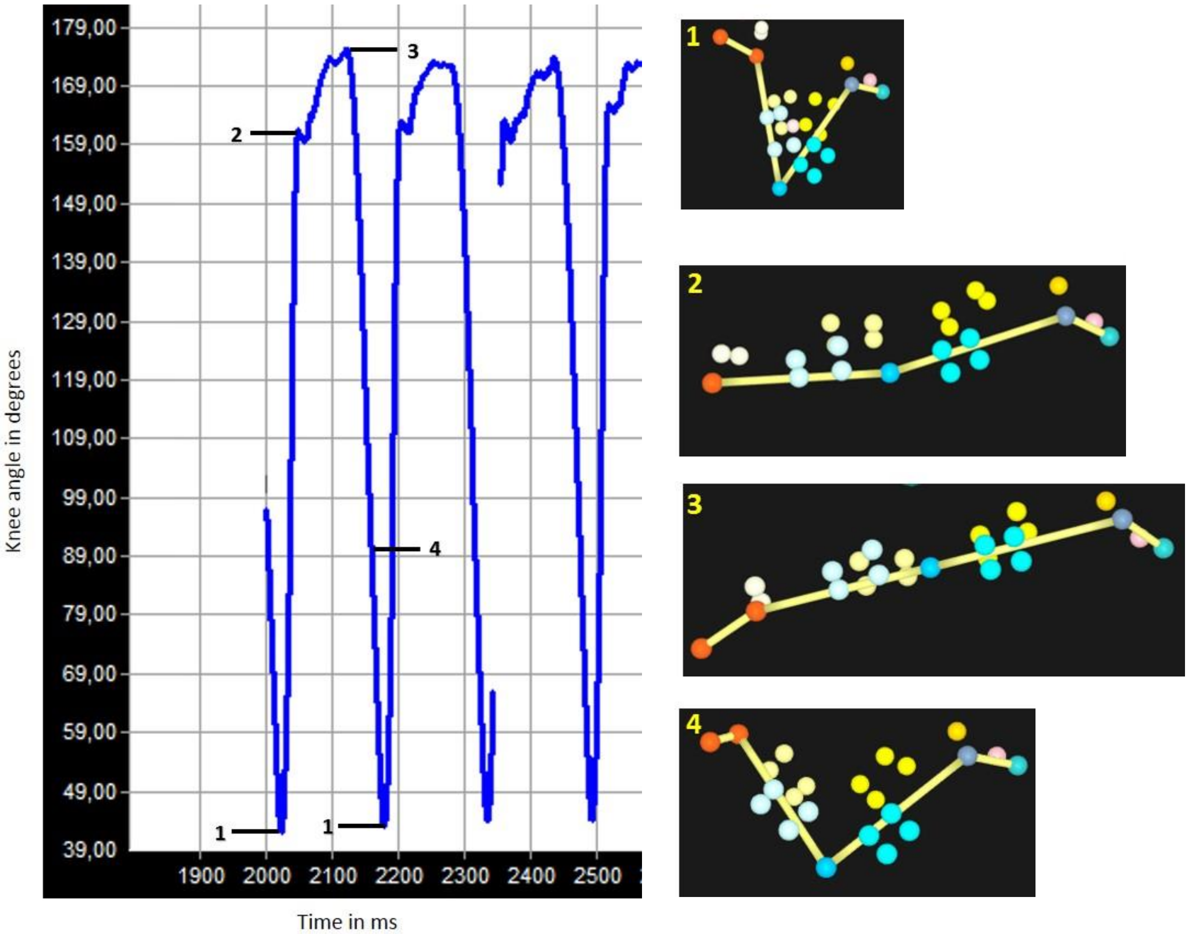

Figure 16. The knee angle and position of the legs at the beginning of each of the four stroke phases during the breaststroke leg kick in elite swimmers.
(1) propulsion, from the smallest knee angle during recovery of the legs until the first peak in knee angle during propulsion; (2) insweep/body undulation/glide from end of phase 1 until second peak in knee angle; (3) first part of the recovery; from end of phase 2 until a 90 degree knee angle; and (4) second part of recovery, from end of phase 3 until legs are back in position 1.

Color coding of the markers on the bone structure from left to right:
● calcaneus and metatarsals; ● lateral femoral condyle; ● trochanter major; and ● iliac crest.

5.3 Muscle activation during submaximal and maximal effort (*Study 3*)

Muscle activation patterns remained similar across the effort levels, but demonstrated longer activation periods relative to the SC with increasing effort. The muscle activation patterns are displayed in Figure 17 (upper limb) and Figure 18 (lower limb) through the different effort levels.

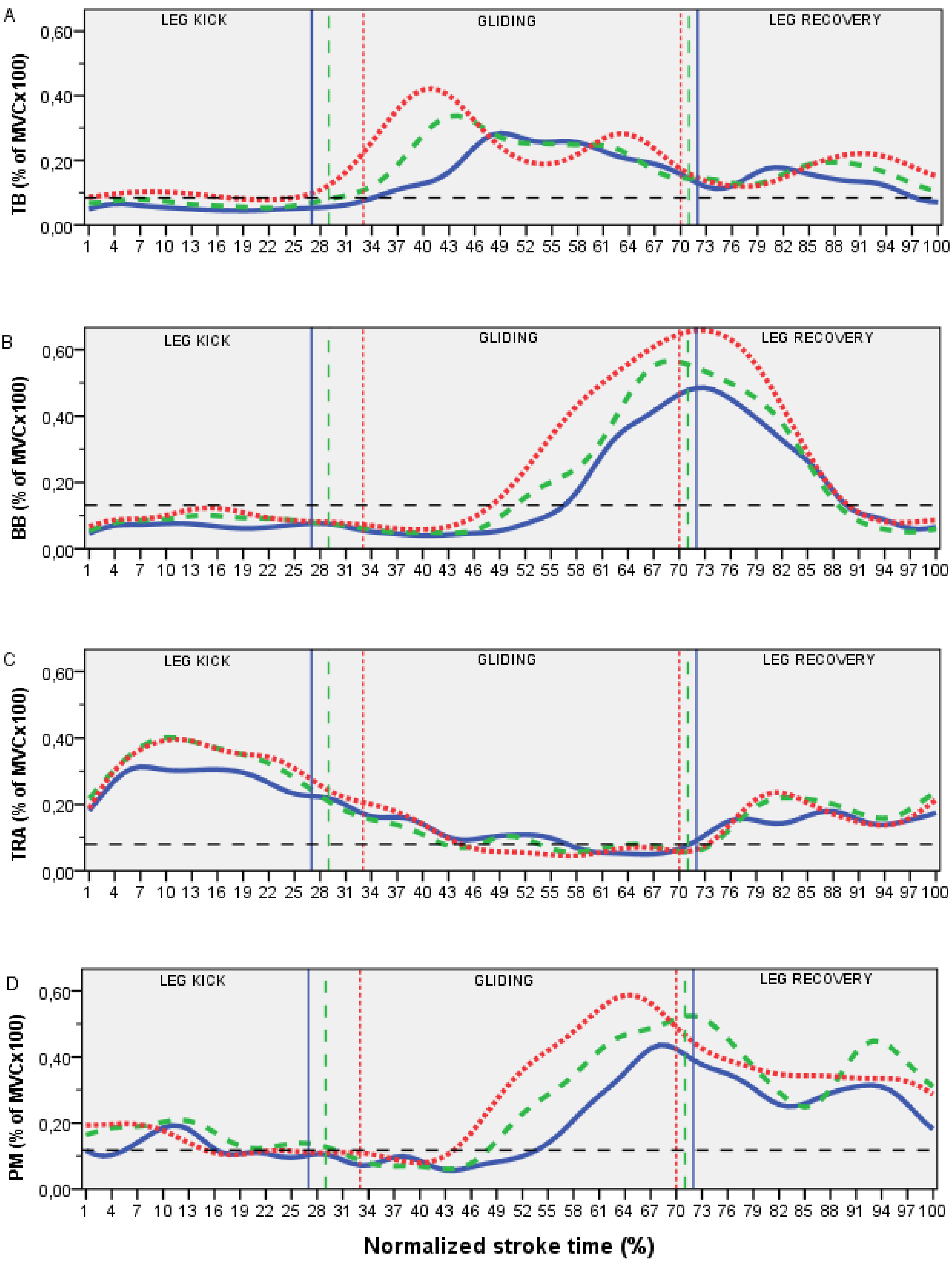

Figure 17. Average muscle activation (avgC) pattern during breaststroke swimming at 60-80-100% of maximal effort for the four muscles of the upper limb during the three phases of the complete stroke cycle.
Amplitude is normalised to the relative isometric maximal voluntary contraction and time is normalised 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).

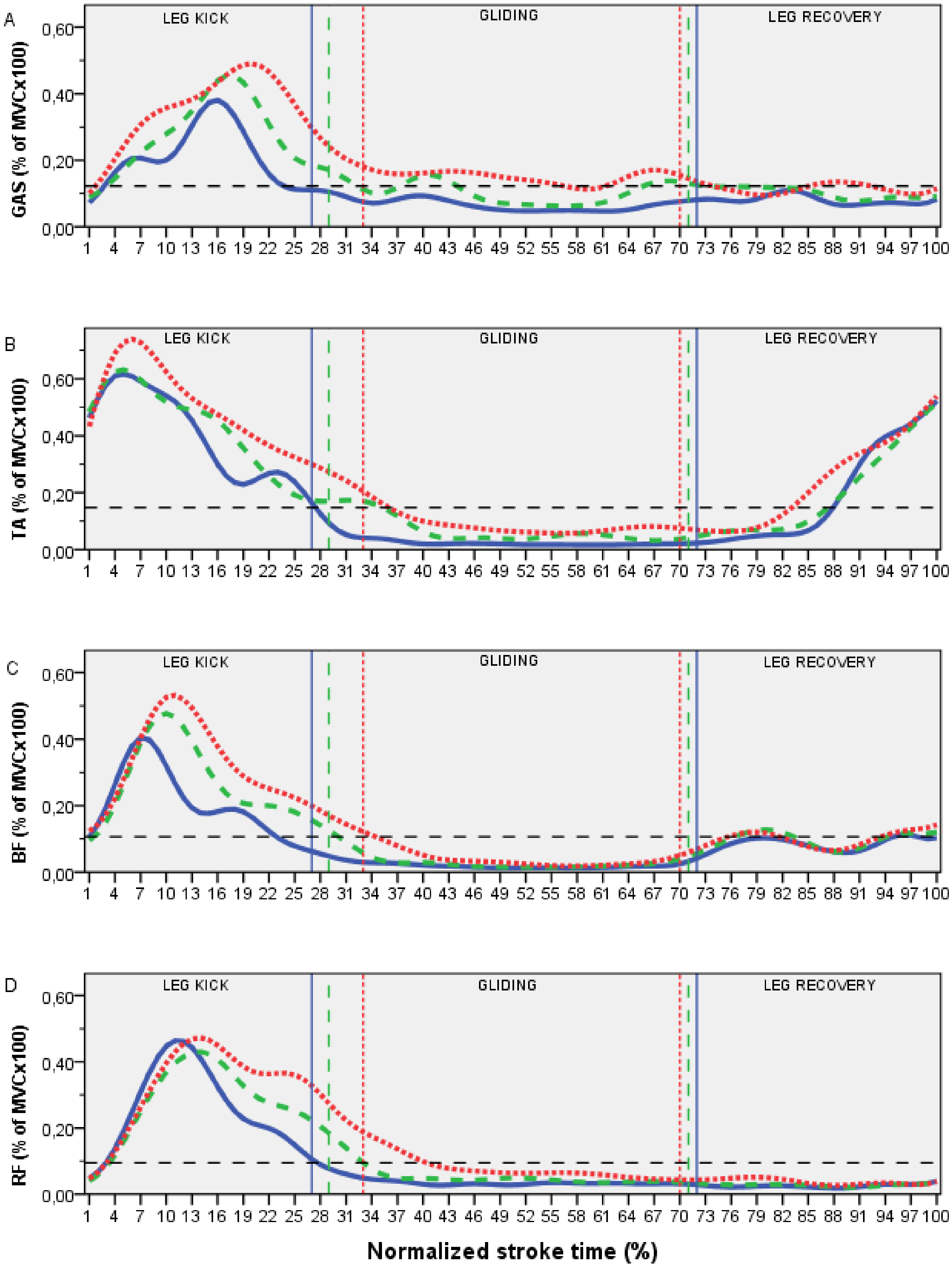

Figure 18. Average muscle activation (avgC) pattern during breaststroke swimming at 60-80-100% of maximal effort for the four muscles of the lower limb during the three phases of the complete stroke cycle.
Amplitude is normalised to the relative isometric maximal voluntary contraction and time is normalised 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.

The sum of total iEMG showed a significant increase with increasing effort for the entire body (sum of all 8 muscles), $F(2, 16) = 28.06$, $p < .001$, upper body (sum of 4 muscles), $F(2, 16) = 19.08$, $p < .001$, and also for the lower body (sum of 4 muscles), $F(2, 16) = 34.17$, $p < .001$. The leg kick 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.

5.4 Muscle activation differences between performance levels (*Studies 4 and 5*)

Distinct differences in muscle activation were found between WC+, WC and NE swimmers.

The results for the muscle activation pattern are presented for maximal effort for one WC+ and one NE swimmer in Figure 19. A representation of when the muscles are active/inactive for one WC and one NE swimmer is presented in Figure 20.

Triceps and biceps brachii

The total average activation for NE swimmers in TB during the leg kick phase was 27.5%, while none of the WC group showed activation (except for one swimmer during the last 6%). Three of the NE also showed activation in TB at the beginning of this phase. WCs activated BB earlier in the gliding phase of the legs than NE, at 52% and 57% respectively. In addition, one WC+ activated the BB 30% into this phase.

Gastrocnemius and tibialis anterior

NE swimmers activated TA for 81.5% of the phase, while WC swimmers showed activation for 68% of this phase. Only the two WC+ and one NE showed activation in GAS at the end of the leg kick. The WCs showed activation in GAS at the beginning of the gliding phase while only one NE had GAS activated. NE swimmers started activating TA at 50% into the leg recovery phase while WC activated TA for the last 45%. In addition two NEs showed coactivation between GAS and TA towards the end of this phase. In contrast to all the other participants, the two WC+ showed no coactivation between GAS and TA during the whole SC.

Biceps and rectus femoris

Only one WC+ started the leg kick phase with coactivation, but all of the swimmers showed coactivation between BF and RF during the leg kick phase. While all of the WCs showed activation in RF during the beginning of the gliding phase, only one of the NEs showed this activation pattern. WCs started the leg recovery phase with a smaller knee angle than NEs (154.6° vs 161.8°) and on average, had BF activated for 40.5% of the leg recovery phase while NEs only showed 29.5%.

Trapezius (pars descendens) and pectoralis major (pars clavicularis)

Six of the swimmers, including both the WC+s, had TRA activated throughout the leg kick phase. WC swimmers showed activation in both muscles for 37% of this phase, NE for 17%, while one WC+ showed activation for 80% of the phase. A large difference between the two WC+ and the other swimmers was seen in the gliding phase of the legs for PM. The two WC+s activated PM for 71% of this phase while the other swimmers activated PM for 54.7%. In addition, two NEs activated PM for only the last 25% of this phase.

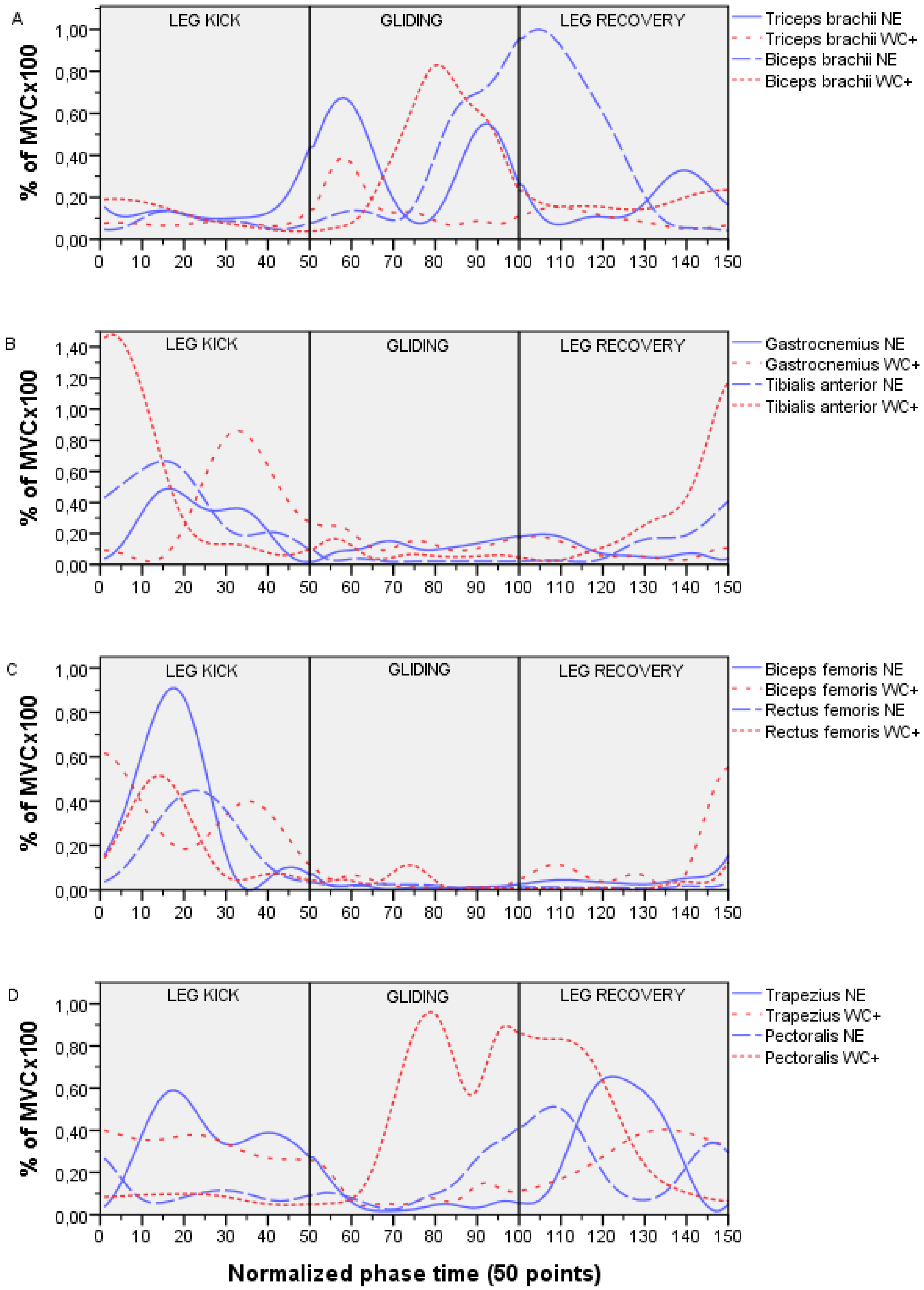

Figure 19. Average muscle activation pattern for one national elite (NE) and one world champion (WC+) swimmer during 100% effort.
Amplitude is normalized to the relative isometric maximal voluntary contraction and time is normalized to the three stroke phases (50 points).

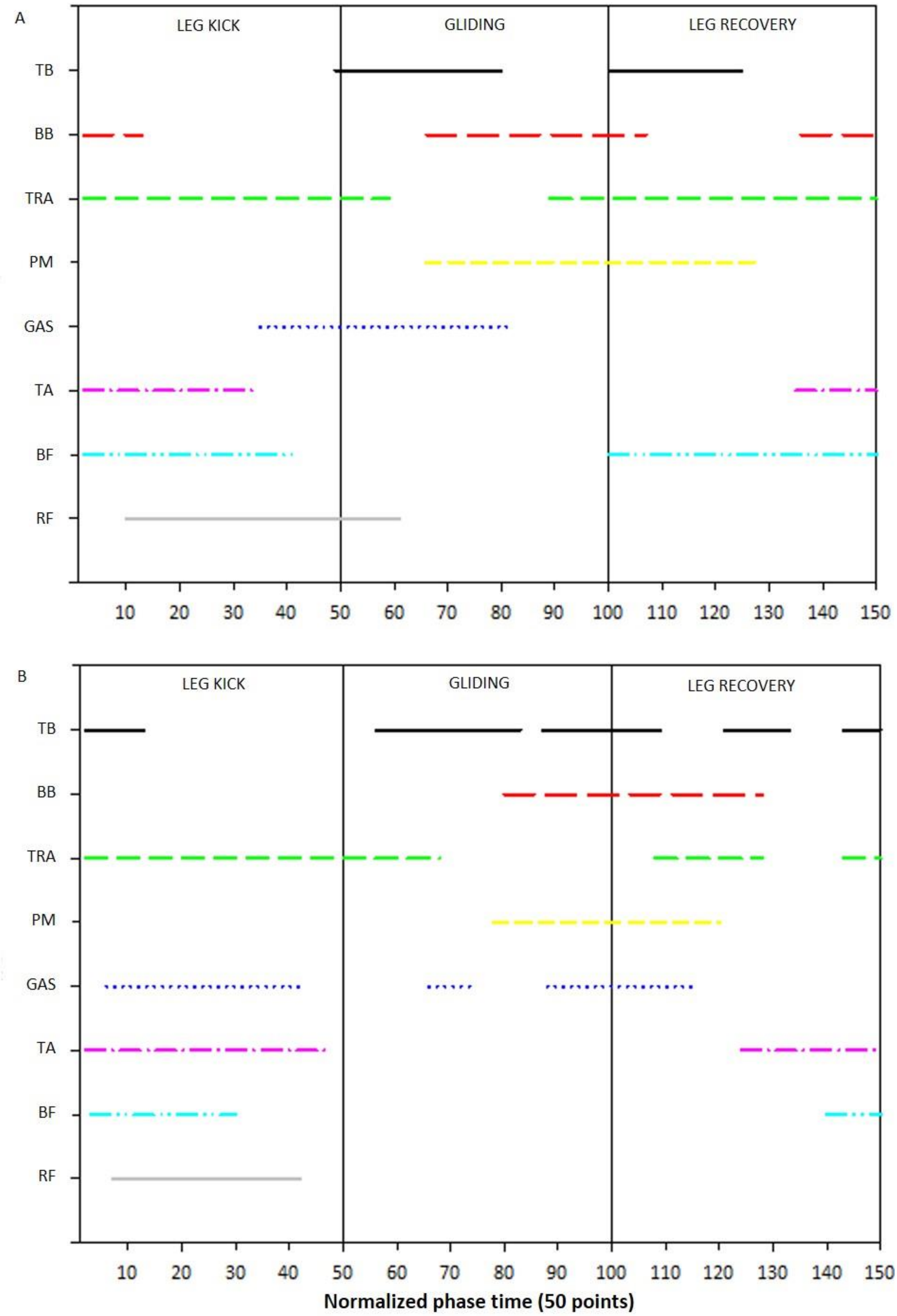

Figure 20. An overview of the muscles participating during the different phases of the stroke cycle at maximal effort for (A) a world-class swimmer; and (B) a national elite swimmer.

Time is normalized to 50 points for each of the stroke phases compiling a complete stroke cycle. Muscles: TB = triceps brachii; BB = biceps brachii; TRA = Trapezius (pars descendes); PM = pectoralis major (pars clavicularis); GAS = gastrocnemius (medialis); TA = tibialis anterior; BF = biceps femoris; and RF = rectus femoris.

5.5 Breaststroke kinematics (*Studies 3-5*)

5.5.1 Kinematics during submaximal and maximal effort (Study 3)

The SC showed a significant decrease in time and cycle length, and a significant increase in velocity and SR with increasing effort levels ($p < 0.01$ – Table 6).

Table 6

Time, length 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 gliding phase

Kinematic variable	60% effort	80% effort	100% effort	*p*-value
Time for leg kick phase (s)	0.50 ± 0.12	0.46 ± 0.09	0.46 ± 0.07	.130
Time for gliding phase (s)	0.87 ± 0.24	0.70 ± 0.16	0.51 ± 0.14	.000 *abc*
Time for leg recovery phase (s)	0.52 ± 0.09	0.45 ± 0.06	0.41 ± 0.06	.001 *abc*
Length of leg kick phase (m)	0.47 ± 0.07	0.49 ± 0.06	0.48 ± 0.09	.850
Length of gliding phase (m)	1.10 ± 0.21	0.94 ± 0.22	0.82 ± 0.16	.014 *a*
Length of leg recovery phase (m)	0.34 ± 0.07	0.36 ± 0.08	0.40 ± 0.09	.103
Total cycle length (m)	**1.90 ± 0.21**	**1.77 ± 0.22**	**1.70 ± 0.17**	.001 *ab*
Velocity in leg kick phase (m/s)	1.05 ± 0.09	1.15 ± 0.20	1.21 ± 0.20	.015
Velocity in gliding phase (m/s)	1.20 ± 0.17	1.29 ± 0.16	1.33 ± 0.16	.010
Velocity in leg recovery phase (m/s)	0.71 ± 0.10	0.82 ± 0.15	0.97 ± 0.23	.016 *b*
Total cycle velocity (m/s)	**1.04 ± 0.13**	**1.13 ± 0.15**	**1.20 ± 0.16**	.000 *abc*
Stroke rate (strokes/min)	**32.20 ± 3.43**	**38.21 ± 3.27**	**42.58 ± 4.36**	.000 *abc*
Knee angle, beginning of leg kick phase (°)	44.80 ± 2.82	43.49 ± 2.55	42.32 ± 2.56	.025
Knee angle, beginning of gliding phase (°)	168.45 ± 7.71	168.29 ± 7.80	168.31 ± 9.32	.988
Knee angle, beginning of leg recovery phase (°)	157.23 ± 5.42	159.97 ± 7.21	158.19 ± 8.12	.521
Largest knee angle during gliding phase (°)	175.22 ± 2.99	175.34 ± 2.68	175.73 ± 4.09	.876

Note: 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%.

The leg kick 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 gliding, knee angle was at its largest. The knee angle stayed relatively constant during this phase, but showed some individual variations based on different executions of the body undulation until the beginning of leg recovery. A significant decrease in time and length was found during this phase, along with a significant increase in velocity ($p < 0.05$) with increased effort.

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

Distinct individual breaststroke techniques were observed among the swimmers, i.e. the knee angle at the beginning of the leg kick slightly decreased with increasing effort (range: 38-46°) and different patterns of knee angle (Figure 21).

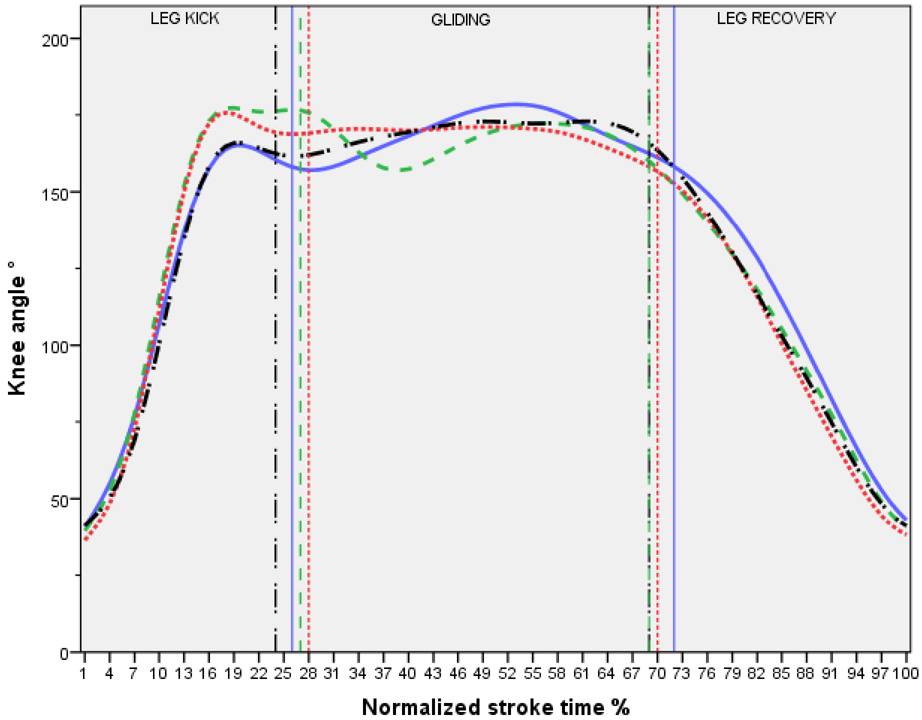

Figure 21. Individual knee angle pattern for four swimmers during the complete stroke cycle for breaststroke swimming at maximal effort.
Time is normalised to the stroke cycle (%). **– swimmer 1**, **– – – swimmer 2**, **····· swimmer 3** and **·---- · swimmer 4**.

5.5.2 Kinematics between different performance levels (*Studies 4 and 5*)

In *Study 4* the total stroke duration ranged from 1.31 s for one NE to 1.58 s for one WC swimmer, with a strong homogeneity among the participants for relative phase durations. The gliding phase, leg recovery phase and leg kick phase represented 41.0 ± 1.0%, 32.7 ± 4.9% and 26.3 ± 4.2% of the total SC respectively. Similar, but different angular patterns were observed for the three participants and the three phases (Figure 22).

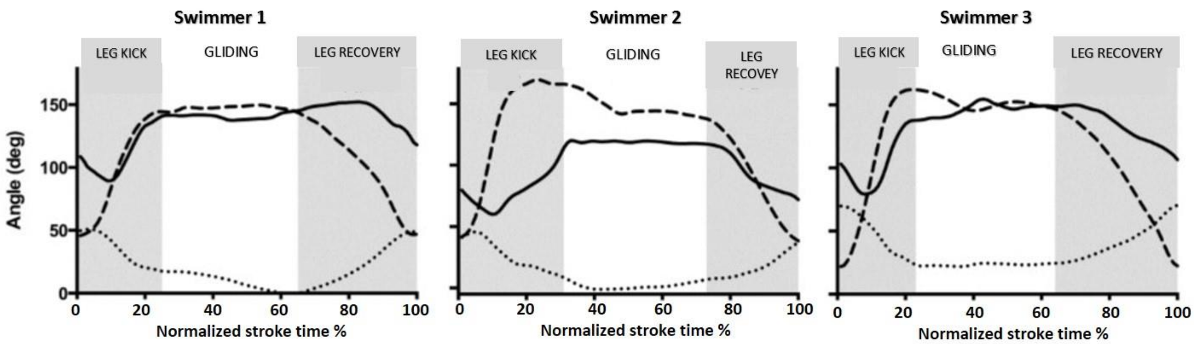

Figure 22. Kinematics of three main joints: the hip (dotted lines); the knee (dashed lines); and the ankle (solid lines) during the three phases of one stroke cycle for the three participants.

In *Study 5,* WCs spent less time during the leg kick phase at 60% and 80% and for the leg recovery phase across all effort levels ($p < 0.05$). The largest difference in mean swimming velocity was found during the gliding phase with WCs being 0.20 m/s faster at 60% of maximal effort and 0.13 m/s faster at 80% and 100% compared to NEs. WCs had a longer cycle length and travelled the furthest during the leg kick and gliding phase. Small differences in the knee angle were found between the two groups with WCs beginning the leg kick phase with a smaller knee angle while NEs started the gliding and leg recovery phase with the largest knee angle.

6 General discussion

Optimal timing of muscle activation and activation patterns is considered to be an important determinant of endurance performance (Castronovo et al., 2013; Figueiredo et al., 2013; Holmér, 1992). This thesis provides new information on the reliability of muscle activation measurements in the water and on how the muscular activation pattern in contemporary breaststroke swimming is affected by both exercise intensity and performance level.

The novelties in this thesis were as follows: 1) We established a reliable method to conduct EMG in water over a prolonged period of time (i.e. 60-90 min) without additional waterproofing of the electrodes. 2) By the phase division of the contemporary breaststroke leg kick a comparison between different technique styles as well as effort and performance levels in terms of muscular activation and kinematic variables was possible in elite swimmers. 3) We produced a neuromuscular description of contemporary breaststroke technique through different effort and performance levels. Since swimming is a complex sport where both the upper and lower limbs work together in complicated ways to produce propulsion and overcome resistance, we provided results from muscle activation and coordination patterns of both limbs. This thesis also demonstrated that WC swimmers seem to use their muscles in a more economical way than NE swimmers.

6.1 Reliability of electromyography in water

In *Study 1* the results indicated a high reliability of the EMG recordings on land before and after 60 min of easy swimming and for a total of 90 min of water submersion. The ICC test values also indicated that all variables can be considered reproducible both in water and on dry land.

Some studies have compared iMVCs on land and in water with different results for the EMG amplitude (Table 2, p. 28), but to our knowledge no previous study has tried to measure the reliability on land before and after a sustained submersion, with water activity in between, which is necessary for conducting swimming experiments. Only two studies have compared land and water EMG in conjunction with water activity. Clarys, Robeaux, and Delbeke (1985) found significantly lower EMG recordings in both the telemetry and tethered EMG systems for the BB in water compared to land measurements after front crawl swimming. Silvers and Dolny (2011) did not measure iMVCs on land before and after aquatic treadmill running, but found no significant difference between EMG recordings from iMVCs on land, in the water after running, and again in the water after running with waterproofed electrodes and connectors. Abbiss et al. (2006) are the only authors known to have compared EMG on land before and after a water submersion, but without water activity in between, and with only 15 min of submersion and waterproofing the electrodes. In agreement with Abbiss et al. (2006), *Study 1* found no difference between land measurements taken before and after submersion.

In *Study 1* the amplitude of the EMG signal was comparable between land and water measurements. However, Veneziano et al. (2006) identified buoyancy as a factor that can reduce the actual force produced in water compared to measuring in air. Other studies have reported buoyancy reducing the EMG signal in water (Clarys, Robeaux, & Delbeke, 1985; Fujisawa, Suenaga, & Minami, 1998; Kalpakcioglu, Candir, Bernateck, Gutenbrunner, & Fischer, 2009; Pöyhönen, Keskinen, Hautala, Savolainen, & Mälkiä, 1999; Sugajima, Mitarai, Koeda, & Moritani, 1996). This may be caused by the reduction in an individual's weight and by the hydrostatic pressure acting on the body during immersion. As in the studies of Pinto et al. (2010), Rainoldi et al. (2004), and Veneziano et al. (2006) we tried to eliminate the buoyancy factor in *Study 1* by ensuring that the muscles were submerged in shallow water (10-40 cm), as well as preventing buoyancy allowing the body to float by the use of an external force (weight) on the participants. This might be the reason why Rainoldi et al. (2004) and Veneziano et al. (2006) measured only the limb that was immersed in water, while Pinto et al. (2010), who measured EMG with the body submerged similar to *Study 1* found the same good reliability between land and water measurements.

Differences in water and air temperature can alter heat transfer in water and lead to lower EMG signal detection (Veneziano et al., 2006). Petrofsky and Laymon (2005) found a significant decrease from land iMVC amplitude after submersion in water at 24°C, of up to 44.8%, but not with water temperatures ranging from 27 to 34°C. *Study 1* eliminated the differences in water and air temperature by ensuring a temperature of approximately 29 °C both on land and in the water.

Another aspect of EMG testing on land and in water that to our knowledge has not previously been addressed in the literature is the size of the electrodes. In all of the studies cited there was either an uncertainty about which electrode size was used or the reported inter-electrode distance varied between 10 mm and 19 mm. All studies used bipolar electrodes. Veneziano et al. (2006) suggested that covering tape in the water and on dry land produces a certain mechanical pressure on the skin and the muscle tissue under the electrode. In terms of increasing this pressure we used waterproof self-adhesive material with a diameter of 57 mm in which the sensors (electrodes) were embedded, with contact surfaces of 10 mm and inter-electrode distances of 20 mm. Furthermore, taping the perimeter around the electrodes with insulating tape was an additional method to prevent water from infiltrating and increasing the pressure on the sensors. A number of studies advise putting additional water-resistant protection on the electrodes while using them in water (Abbiss et al., 2006; Carvalho et al., 2010; Rainoldi et al., 2004; Silvers & Dolny, 2011; Veneziano et al., 2006). Rainoldi et al. (2004)

showed that submersion in pool water without waterproofing the electrodes and having free electrode cables resulted in a decrease in EMG amplitude during submaximal isometric contractions (50% of iMVC) of 6.7% compared to dry conditions for the BB. The power spectrum was also altered by moving water compared to motionless water. Carvalho et al. (2010) found that the water-resistant protection did not affect EMG amplitude on land, but without its use in water the signal amplitude decreased by nearly 50%. However, we found that the measurements in *Study 1* were reliable without additional waterproofing of the electrodes. As long as buoyancy (using additional weight to prevent the body from floating), temperature (approximately 29 °C and same for land and water), and cable artifacts (by fixing loose cables with extra insulating tape along the participant's body) are accounted for, using large waterproof electrodes and taping the perimeter is sufficient to prevent water infiltration and provide a reliable method for conducting EMG in water over a prolonged period of time (i.e. 60-90 min). This method can therefore be used not only for measuring elite and novice swimmers, but also for conducting experiments in other aquatic sports, and for developing exercises for prevention and rehabilitation of injuries and chronic diseases.

6.2 Phases in breaststroke swimming

In *Study 2* we developed a specific method for analyzing the different phases of the contemporary breaststroke leg kick in order to account for different technique styles used by elite competitive swimmers. This phase division was adapted in *Studies 3-5* to allow a global understanding of what is occurring during the traditional phases of propulsion, glide and recovery (Seifert, Leblanc, Chollet, & Delignieres, 2010) with regard to muscular activation pattern.

The literature identifies several different models for identifying the phases in breaststroke swimming (2.3.3, p. 12); these models have different numbers of phases regarding the arm pull, leg kick or both. Colman et al. (1992; 1998) digitized 12 images with stick figures to divide the stroke into 8 phases. The most recent method for investigating arm-leg coordination in the flat breaststroke came from Chollet et al. (2004), who divided both the arm pull and leg kick into five separate phases based on effective glide, propulsion, leg insweep and recovery. The same model was later used by Leblanc et al. (2005) and Seifert et al. (2005) to evaluate flat breaststroke technique in recreational and elite swimmers. The challenge with this method for analyzing the breaststroke kick in terms of phases is the assumption that all breaststroke kicks finish with the feet actively coming together during the insweep, followed by a streamlined glide and active knee bend to start the recovery. When applying this method to elite contemporary breaststroke swimmers in *Studies 2-5*, the phases could not be accurately separated due to differences in their technique, influencing both the insweep and knee bend during the leg recovery phase. Instead of a more traditional up, out, in and glide type of kick, these elite swimmers performed a more rounded kick where the feet were not always being actively pushed together during the insweep. They rather kicked their legs into an up-kick motion. The position described by Colman et al. (1998) (legs parallel to each other and in line with the hips) would provide a more distinct parameter that could be used for analyses across different technique styles. Chollet et al. (2004) described the first part of the recovery starting with knee flexion and forward movement of the feet. However, the elite swimmers tested in *Studies 2-5* showed a knee flexion during the gliding and a consequent forward movement of the feet was observed. In addition, there was still no sign of an active recovery of the legs until later in the SC. Therefore, the phase division from *Study 2* that was adopted in *Studies 3-5* seems to provide a more appropriate method for phase division in the elite contemporary breaststroke leg kick. Further, this method could be used across swimmers with different technique characteristics. In addition, when analyzing the muscular activation pattern, introducing more phases into the SC can generate additional noise. Since each SC takes about 1.5-2.0 s to complete and is based on different coordination modes the phases could overlap.

The leg action plays a central role in *Studies 2-5*. Breaststroke has been identified as the swimming stroke where the major source of forward propulsion stems from the lower limbs (Mason et al., 1989). Further, the leg recovery in some swimmers can lead to an almost complete stop in the SC (Maglischo, 2003). To obtain a clear and fixed starting point for identifying phases, we therefore chose to look at the leg kick. The use of distinct angles and marker trajectories helped to provide clear reference points for identification and synchronization of the movement into phases.

From all the different phase divisions applied by practitioners and researchers it is difficult to establish one ideal method. They all contribute to a better understanding of the breaststroke kinematics and movements and should rather be selected by the primary goal for the outcome, e.g. teaching breaststroke technique, analyzing SC kinematics, motor patterns, inter-limb coordination, IVV or muscular activation patterns. In this context, *Study 2* created a specific method for analyzing and evaluating the elite contemporary breaststroke leg kick that encompasses the different swimming styles and can be adapted for investigating muscular activation and coordination. This method could further be expanded to create phases for the contemporary breaststroke arm pull in order to, for example, create an index for studying inter-limb coordination.

6.3 Lower limb muscular activation and kinematics

As expected, the muscles of the lower limb showed the highest activation during the leg kick phase across all swimmers and effort levels in *Studies 3-5*, while little activation was found for the most part during the gliding phase. Important intra-subject and inter-subject variability was observed among the swimmers.

Time-motion and muscular activation patterns indicated typical coordination patterns among the swimmers. At the beginning of the leg kick phase the feet take support of inert masses of fluid in order to generate propulsive forces with TA activation. The phase then started with hip and knee extension through activation in RF and BF, followed by ankle extension towards the end with activation in GAS, as observed during on-land vertical jumps performed by swimmers (Eloranta, 2003). This simultaneity has also been observed in frog swimming propulsion, where lower limb joints are mobilized simultaneously in order to produce maximal force at the beginning of the kick (Nauwelaerts, Stamhuis, & Aerts, 2005). Likewise, the simultaneous coordination adopted by breaststrokers may produce high forces at the beginning of this phase. Moreover, total knee extension was completed at approximately 20% of the total SC duration, inducing important antero-posterior foot velocities (between 3.1 m/s to 4.7 m/s) related to whole body progression. Similar results were observed in rowing, where the lower limb extension is characterized by a high lower limb velocity which accelerates the entire body (Celentano, Cortili, di Prampero, & Cerretelli, 1974). The synchronous coordination adopted in breaststroke allows the swimmer to obtain important foot velocities and the foot whip at the end of the kick is the optimal strategy to produce important power during the push, using the feet as paddles (Maglischo, 2003).

Weaker muscular activations were noted during the gliding phase compared to the leg kick phase in *Studies 3-5*, in which drag was strongly reduced compared to the other phases of the breaststroke (Kent & Atha, 1975). A similar decrease was found in breaststroke for the main lower limb muscles (Ikai, Ishii, & Miyashita, 1964). Moreover, the low activation observed in RF was comparable to that described by Yoshizawa et al. (1978) in the continuous breaststroke technique. Also, in ergometer rowing (Turpin, Guével, Durand, & Hug, 2011) and on-water rowing (Guével et al., 2011), this phase (recovery in rowing) showed low activations for the lower limb muscles. It can be considered a “resting phase” with respect to the work of the leg muscles, and as a way to reduce the energy cost, as seen in marine mammals (Williams et al., 2000) and in fish (Videler & Weihs, 1982; Weihs, 1974) by taking advantage of the created propulsion and utilizing it for gliding in order to conserve oxygen and maintain speed. In other swimming strokes, including front crawl and backstroke, the leg kick is rarely divided into a gliding phase since the purpose is to generate propulsion through both the up and down phases of the kick. However, when swimmers are performing at lower speeds, the lower limb muscles are less activated and used primarily for stabilizing the body (Lewillie, 1973,) with a lower kicking frequency.

The last part of the movement is the leg recovery phase in order to prepare the lower limb for a new SC. Despite the non-propulsive leg action during this phase, important muscular activations were present in BF and TA as noted by Yoshizawa et al. (1978). During terrestrial walking, muscular activations are important during the stance phase, with negligible solicitations during the swing phase (Ounpuu, 1994). In water walking, a continuous muscle activation called "tonic pattern" appears to overcome the drag (Masumoto & Mercer, 2008). Similar results were observed in breaststroke, underlying the specificity of the aquatic environment to leg recovery with high muscular activations, possibly due to water drag.

6.4 The effect of effort level on muscle activation and kinematics

6.4.1 Kinematics

The significant decrease in SC length and the increase in velocity and SR with increasing effort are in accordance with previous studies performed in competition analysis where the short distance (100 m) showed the highest velocity and SR, and the shortest SC length, compared to the longer 200 m distance (Craig et al., 1985; Thompson, Haljand, & MacLaren, 2000). This is also in accordance with observations for front crawl and backstroke (Chollet, Pelayo, Tourny, & Sidney, 1996; Craig et al., 1985; Haljand, 2014). However, when comparing different elite swimmers competing in a particular distance, it is more a specific and individual combination of SR and SL that will determine the velocity (Craig et al., 1985; Hellard et al., 2008).

Since absolute phase time and length remained similar during the leg kick phase despite increasing effort, this might indicate that swimmers also executed a strong propulsive kick 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 6, as well as better upper body streamlining at the beginning of this phase, suggesting that they had a better working economy with increasing effort.

The longer gliding during breaststroke is unique compared to the other competitive swimming strokes even though, for example, the front crawl often shows a catch-up coordination at lower speeds with a lag time between the propulsive phases of the two arms (Chollet, Chalies, & Chatard, 1999). A well-known strategy, which was also seen among the elite swimmers in *Study 3*, is therefore to decrease the time spent in this phase in order to increase velocity with increasing effort.

There was a significant decrease in absolute time and an increase in velocity with increasing effort while length remained constant during leg recovery. This might indicate a more powerful recovery as shown in the increased muscular activation and a better execution in maintaining the speed and increased momentum generated from the upper body propulsion through a more continuous coordination mode.

6.4.2 Muscular activation

The muscle activation patterns remained similar through the different effort levels. However, the muscles showed longer periods of activation relative to the SC and increased amplitude when velocity and effort increased. This was also reflected in the significant increase in iEMG for the SC with increased effort for all muscles except TRA. This might indicate that the swimmers were executing a good upper body streamline position at lower effort levels with the use of TRA. For the other muscles our results are similar to the findings of Turpin et al. (2011) for the rowing cycle, where significant increases 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 unchanged. In contrast, Schache, Dorn, and Pandy (2013) found a change in muscle coordination from jogging (ankle plantar flexion muscles dominated) to sprinting (hip flexor and extensor muscles became more activated). 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), which is absent during swimming due to the horizontal position in the water and the lack of solid ground for contact.

In one of the older studies in breaststroke, Lewillie (1973) found that when speed increased from slow to sprint, TB activity more than doubled in amplitude in relation to iMVC. An increase in amplitude was also found in *Study* 3, of about 25% between 60% and 100% effort. This difference could be related to Lewillie's (1973) findings regarding starting at a lower effort level, as well as the methodology for iMVC testing. The swimmers reached 120% of iMVC during sprint speeds while in *Study 3* the swimmers reached about 45%. In agreement with Lewillie (1973), RF did not show increased amplitude with increasing effort, indicating that RF contribution is also high at lower effort levels in order to provide a strong beginning to the knee extension for a powerful leg kick. However iEMG and length of activation increased with effort level showing that RF contributes more and longer to increase velocity during the leg kick phase with increased effort.

Similar to the findings of Yoshizawa et al. (1976), *Studies 3-5* found that propulsion in the breaststroke kick started with high activation in TA through the first part of the kick, indicating that the dorsiflexion of the foot was maintained to create a good grip on the water and obtain large propulsive forces across all effort levels. During leg extension at all effort levels, the coactivation in BF and RF resulted in high power in the hip and knee. Additionally, the high activation in GAS towards the end of this phase indicated a shift towards ankle plantar flexion to bring the feet together with high velocity. The TRA showed its highest activation during this phase for all effort levels indicating a strong contribution to maintaining the upper body in a streamlined position. The PM activated earlier at 80% and 100% levels when compared to 60%. This indicates a stronger contribution in stabilizing the arms over the head to improving the streamlining of the upper body with increased effort as well as a more continuous coordination mode between the arms and legs (Maglischo, 2003). Since forward propulsion during this phase is generated by the legs, the minimal activation in TB and BB suggest an economical use of these muscles, preparing them for the next phase. However, increased effort enlarged the activation in these muscles to more than double for TB and almost double for BB. This implies that the swimmers begin their reach and pre-activation for the arm pull earlier with increasing effort in order to switch to a more continuous or superposed stroke coordination.

As identified by Yoshizawa et al. (1976), activation in RF in *Studies 3-5* during the first half of the glide indicated that full knee extension occurred after the completion of the insweep of the feet (Table 6), where the largest knee angle occurred during the gliding phase. There was also an increase in RF activation between 60% and 100% effort, which could be related to the higher activation observed during the leg kick 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 gliding at around 65% into the SC. The activation observed in GAS at maximal effort also suggests a more active role in streamlining the feet during gliding in order to actively decrease the drag. The longer gliding in breaststroke may explain the low activation levels of the other leg muscles. The TB, BB and PM showed peak amplitude and iEMG as they act as the prime movers for generating propulsion and increasing velocity through this phase. The TB is activated first and earlier with increasing effort indicating a further arm extension, reaching forward and out in the water to generate an even longer arm pull and activation during the outsweep. At 100% effort, TB started activating during the leg kick phase while at 60% and 80% effort activation began during the gliding phase. This might indicate an earlier and more active role in decreasing the time gap between the overlap in propulsion from the lower and upper limbs. The coactivation in TB and BB towards the end of this phase was also found by Yoshizawa et al. (1976), showing an active flexion of the forearm. In addition, Yoshizawa et al. (1976) found higher and earlier activation for BB during the arm-pull in Olympic swimmers, as we found with increasing effort, indicating an earlier elbow flexion and orientation of the propulsive surface of the upper limbs earlier in the SC. During the propulsive contribution of the arm pull our results showed that TRA went into rest at 100% effort more rapidly and for longer compared to both 60% and 80% effort, indicating an earlier start of upper body propulsion.

During leg recovery, important muscular activities were found, which are involved in bringing the legs quickly back to the beginning of the cycle for the next leg kick. Knee flexion was initiated through activation in BF and continued activation in GAS indicated a continued plantar flexion of the ankle to reduce drag. High activation in 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 leg recovery indicated that other muscles also contribute in this phase, for example the gluteal muscles, semimembranosus and semitendinosus, as observed by Onishi et al. (2002) during knee flexion or the adductor magnus as observed in running (Wiemann & Tidow, 1995). The significant increase in activation in BB and PM during this phase with increased effort indicates a more forceful insweep of the arms with high hand velocities.

Most training sessions for swimmers are performed at less than maximal effort. From the point of view of muscular activation patterns, breaststroke swimmers use the same temporal and spatial organization of the motor output during training and competition. However, it should be kept in mind that muscle activation patterns are also linked to the muscle activity level. Hence, the increase as effort level increases should be considered in situations such as specific endurance and power training for the muscles.

6.5 The effect of performance level on muscular activation and kinematics

Distinct differences in muscle activation pattern and coactivation were found between WC+, WC and NE swimmers in *Studies 4-5* and are outlined in the following paragraphs.

6.5.1 Triceps and biceps brachii

The most distinct differences in muscle activation patterns between the swimmers were found for TB and BB. The fact that no WC showed activation in the TB until the last 6% of the leg kick phase, while three of the NEs showed activation at the beginning of this phase indicates that NEs start their leg kick phase before the upper body has reached the full streamlined position as seen in the motion capture. In addition, the activation in TB in NEs during this phase indicates that they are using TB during the streamline position of the upper body in contrast to WCs who are able to rest this muscle and save energy during the non-propulsive arm phase.

According to Maglischo (2003) the outsweep of the arms during breaststroke is a non-propulsive phase and the forward velocity of the body will decelerate through this phase. Therefore, the main purpose of the outsweep is to align the hands in a backward-facing position as soon as possible through a flexion of the arms at the elbows, initiating BB activity and placing them in a position to allow acceleration through the insweep. WCs showed an activation in BB at 52% into the gliding phase of the legs, NEs started activating later at 57%, while one of the WC+s activated at 30% into this phase, indicating an even earlier elbow flexion and orientation of the propulsive surface, similar to Yoshizawa et al. (1976).

While the other swimmers maintained high activation amplitudes in both muscles, one WC+ had very high activation in TB and very little activation for BB (middle distance swimmer - 100m (WC+1)). The other WC+ had very high activation in BB while very little activation was observed for TB (sprinter - 50m (WC+2)). Both swimmers started the arm pull by activating TB as they reached their arms forward to extend their SL. WC+2 activated TB 6% before the end of the leg kick phase while WC+1 activated 5% into the gliding phase. These aspects have been identified, through the coordination of the arms and legs, by Maglischo (2003) as continuous and superposition timing. The superposition timing used by WC+2 is characterized by the beginning of the outsweep occurring before the legs come together, while the continuous timing of WC+1 begins with the outsweep as the legs come together. These two timing techniques also correspond to the swimmers' primary competition distances where WC+2 is a 50 m breaststroker while WC+1 is a 100 m breaststroker (Chollet & Seifert, 2011).

In addition, WC+2 had high activation in BB early during the gliding phase, indicating an earlier change of arm direction to generate forward propulsion and lift (Yoshizawa et al., 1976). This could also be a strategy for WC+2 to generate a more explosive stroke with a higher lift of the upper body out of the water in order to bring the hands explosively forward over the water surface. In addition, WC+2 was a more upper body swimmer who generated less velocity during the leg kick phase than WC+1. WC+2 then compensated with a higher SR, shorter SL and more explosive arm movements during the gliding phase of the legs. WC+1 used a flatter stroke with a more shallow kick (ankle depth) and less vertical hip movement as identified in the motion capture and therefore was not required to put the same amount of activation on BB. This could also be an advantage for WC+1 in that it generates high velocity during the leg kick and can therefore maintain streamlining for a longer period of time with longer SL and lower SR, in order to swim more economically and maintain the stroke for longer distances.

6.5.2 Trapezius (pars descendens) and pectoralis major (pars clavicularis)

Of the eight muscles tested, all swimmers showed the longest periods of activation for TRA and PM relative to the SC. Six of the swimmers, including both WC+s, had TRA activated throughout the leg kick phase, suggesting that TRA is activated to maintain upper body streamline position during the leg kick. In addition WCs had activation in both PM and TRA for 37% of this phase, NEs for 17%, while one of the WC+s showed activation in both muscles for 80% of the leg kick phase, revealing that WCs may further optimize and lengthen the upper body streamlined position.

Colman et al. (1998) and Van Tilborgh et al. (1988) found that the hand insweep is often the most propulsive phase of the arm stroke. This can be linked to the activation in PM, which is a powerful muscle that generates forward propulsion from the upper limb. A large difference between the two WC+s and the other swimmers was seen during the propulsive arm pull (gliding phase of the legs) for the PM. The two WC+s activated their PM for the last 71% of this phase while the other swimmers activated PM for only 54.7% ± 10.5% on average. In addition, three of the NEs did not start activating PM until the last 25% of this phase. This implies that the WC+s are able to "grab" the water earlier and generate higher forward propulsion from the arm pull while the legs are gliding and may also indicate that they use a more continuous coordination mode as identified by Yoshizawa et al. (1978) when comparing the glide and continuous stroke.

6.5.3 Gastrocnemius and tibialis anterior

All swimmers started the leg kick phase with activation in TA, indicating that they had a good dorsiflexion of the ankle at the beginning of this phase as identified in *Studies 3-5*. In contrast to Yoshizawa et al. (1976), who found longer activation for TA in Olympic swimmers, allowing a longer dorsiflexion of the foot, the NEs in *Study 5* showed a longer TA activation than the WCs. The shorter TA activation found in WCs could be explained by the evolution in breaststroke technique where today's style is categorized by a deeper leg extension followed by a rising undulation of the feet during the insweep of the feet (Seifert et al., 2011) as identified in *Study 2*. Motion capture from recent international championships also supports the hypothesis that swimmers are no longer using dorsiflexion throughout the leg kick phase in order to create lift, but instead plantar flexion towards the end to ensure high foot velocities with less drag and a rising of the feet. Further research is needed in order to confirm this phenomenon and its contribution to lower drag or higher propulsion.

The better timing of the use of GAS found by Yoshizawa et al. (1976) for the best swimmers, which prevented the premature plantar flexion of the foot seen in poor swimmers, resulting in a less effective kick, was still present in both groups. All WCs, but only one NE, showed activation in GAS at the beginning of the gliding phase, suggesting that the WCs may be better at streamlining their ankles to reduce resistance during the gliding phase, as observed in *Studies 3-5* during 100% effort.

Yoshizawa et al. (1978) investigated Olympic swimmers and found strongly activated TA at the beginning and during the leg recovery phase. By comparison, no swimmers in *Studies 3-5* showed activation in TA during the beginning of this phase, indicating that the breaststroke technique has changed and that today's technique takes further advantage of the up-kick motion, with plantar flexion of the ankle to further reduce drag as identified in *Studies 3-5*. This is also in accordance with the technique described by Maglischo (2003), in which the lower legs and feet are recovered forward, and just before the feet reach the buttocks they are swept outwards and forward indicating a contribution from TA. NEs showed activation for TA during the last 50% of this phase while in WCs it occurred over the last 45%, indicating an earlier transition from plantar flexion to dorsiflexion of the ankle in NEs as seen in the motion capture. This indicates that the WCs use their muscles in a better way to reduce drag during leg recovery and have a quicker transition from plantar flexion to dorsiflexion. This could also be a reason why they spend less time in this phase. In contrast to the six other participants the two WC+s showed no coactivation in GAS and TA during the whole SC, indicating an optimal movement economy between dorsi- and plantar-flexion of the ankle in order to generate propulsion and reduce drag. This is in accordance with studies conducted in walking (Hortobágyi et al., 2011) and running (Frost et al., 2002; Frost et al., 1997; Moore, Jones, & Dixon, 2014), where it was found that excess coactivation was an inefficient process that increased the metabolic cost. In cycling, excess coactivation was observed in less skilled cyclists, but not in elite cyclists (Chapman et al., 2008).

6.5.4 Biceps and rectus femoris

In *Study 5*, all of the swimmers showed coactivation between BF and RF during the leg kick phase, indicating that knee extension was generated with high power. One of the WC+s started this phase with coactivation in BF and RF. Muscle coactivation between quadriceps and hamstrings is considered very important for knee joint stabilization during many athletic activities (Kellis, 1998). In *Study 4* high angular velocities for the knee during the leg kick in breaststroke corresponded to a powerful extension and could be considered a strategy for better controlling the precision and safety of the movement (Guignard et al., 2015b).

All of the WCs, but only one NE showed activation in RF during the beginning of the gliding phase, which may indicate, as shown in Yoshizawa et al. (1976), that full knee extension occurs after the completion of the insweep in the legs for WCs. For the WCs this might point to an active strategy in performing a body undulation with the hip slightly flexed and with the buttocks lifted up towards the water surface as seen in the motion capture.

Cappaert, Pease, and Troup (1996) and Leblanc et al. (2005) found that the best swimmers spent a shorter time in the leg recovery phase. This is in agreement with our data that showed a significantly shorter time spent in the leg recovery phase for WCs compared to NEs. This may be because WCs showed longer activation in BF during the leg recovery phase with 40.5% while NEs only showed activation for 29.5% of this phase. This indicates that WCs use BF more actively to bring the heels up to the buttocks for a quicker leg recovery, as indicated in Yoshizawa et al. (1976), to ensure minimum forward flexion of the thigh to keep water resistance to a minimum.

In summary, our results have provided descriptions of contemporary breaststroke technique from a neuromuscular perspective in elite swimmers and showed that a distinct difference in muscle activation pattern exists between swimmers at different performance levels. The best swimmers began their arm pull at the end of the leg kick phase with activation in TB to extend their reach during the outsweep, followed by an early catch with activation in BB while thereafter initiating an early activation in PM for a powerful insweep. In WC swimmers, muscle activation for the legs was characterized as follows: GAS towards the end of the leg kick, RF at the beginning of gliding and an earlier activation in BF during leg recovery. WC swimmers also took a significantly shorter time for the leg kick and leg recovery phases than NEs. In addition, the longer coactivation and less economical use of the muscles found in NE can relate to a greater metabolic cost while swimming, which could be detrimental to performance (Moore et al., 2014). This knowledge can be used not only for improving training efficiency and technique in competitive swimmers, but also for teaching beginners, and designing applicable weight training and dry-land programs.

6.6 Limitations of the studies

Limitations in the studies on 3D kinematics include the fact that we only had cameras located under water. This meant that markers on the upper body and arms went out of the water during certain parts of the SC, including arm recovery and breathing.

Swimmers at this level could be expected to have a higher swimming velocity at the different effort levels than was shown in *Studies 3 and 5*. An explanation 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 than for swimmers with no markers. 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.

The EMG equipment allowed for continuous measurement of eight muscles. These eight muscles were selected based on previous research identifying them as important for performance in breaststroke (Table 3 and Troup, 1999). In order to fully understand the muscular activation pattern and coordination of contemporary breaststroke, more muscles involved in generating propulsion and positioning of the limbs should be investigated.

In addition, *Studies 2-5* had a limited sample size and only included elite swimmers. This only allows limited conclusions to be reached.

6.7 Practical applications and future research

6.7.1 Scientific point of view

The practical applications of the reliable method for acquiring EMG during a prolonged submersion using an original electrode configuration ensuring greater contact surface with the skin without additional waterproofing, as established in *Study 1* for conducting EMG in water, has already provided additional research outcomes (Guignard et al., 2015a; Guignard et al., 2015b). This method applies not only to measurements in elite and novice swimmers, but also to experiments in other aquatic activities, e.g. water polo, water running, synchronized swimming and water aerobics, and to the development of exercises for the prevention and rehabilitation of injuries and chronic diseases that require prolonged submersion.

The 3D motion capture system with automatic tracking used in *Studies 2-5* provides new possibilities for conducting large scale kinematic studies in water and the inclusion of additional SCs during swimming due to the decrease in processing time.

At present there is no index of inter-limb coordination for contemporary breaststroke swimming. The new phase division for the contemporary leg kick could be taken as a foundation with which to further investigate the phases of the upper limb in order to develop such an index.

Further results and methodology from the *Studies* presented throughout this thesis have also opened up new research questions which will be further presented in the next section (6.7.2).

6.7.2 Practitioners point of view

Measuring muscle activation and coordination patterns and kinematic variables is important in evaluating swimming technique and performance. While kinematics can be roughly observed by coaches, the use of kinematic analysis in 3D with automatic tracking makes the evaluation of swimming movements more accurate and detailed. Such analysis provides the coach and athlete with numbers and values that can be used to further improve performance, rather than just a visual inspection of what might be right or wrong. Without kinematics, it is not possible to observe muscle activation and coordination patterns. Therefore, the results presented in this thesis can provide practitioners with important information regarding swimming technique.

In order to have efficient propulsion and good working economy the right muscle activation and coordination is highly important. This thesis revealed that distinct differences exist between international medalists and elite swimmers in terms of muscle activation pattern, coactivation and kinematic variables, which can help to provide performance discriminators. The practical implications of these findings may contribute to enhanced performance in today's upcoming breaststroke swimmers. The differences between swimmers at different performance levels found in *Studies 4-5* have been confirmed through the use of EMG. This suggests that coaches and swimmers should focus on the following points from EMG and kinematics when evaluating breaststroke technique:

- An early activation in BF during leg recovery in order to decrease the time spent in this phase.
- A late and quick activation in TA during leg recovery in order to reduce drag and premature dorsiflexion of the foot.
- An early activation in BB in the arm pull for elbow flexion in order to generate earlier arm propulsion and a more continuous stroke pattern at maximal effort.
- An active use of GAS during the gliding phase to maintain a more streamlined position of the feet.
- Activation in RF during the beginning of the gliding phase for full knee extension to occur after the feet insweep. This might point to an active strategy for performing body undulation.
- An earlier and longer PM activation during the leg recovery phase (arm propulsive phase) to "grab" the water earlier and generate higher forward propulsion from the arm pull and use a more continuous coordination mode.
- An activation in TRA during the leg kick phase in order to maintain upper body streamline position.
- Creation of a small knee angle during the beginning of leg propulsion (leg kick phase) in order to generate a longer propulsive path for the leg kick.
- Avoidance of excessive coactivation in TA and GAS during the SC, and excessive use of TB during the leg kick phase (non-propulsive arm phase), which may cause an earlier onset of muscular fatigue during training and competition.

The results of this thesis show the recruitment pattern of international medalists and imply that swimmers could benefit from activating certain muscles more, less, earlier or later. However, such feedback about muscle activation might be difficult to interpret and apply during swimming. Using 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 look at the common techniques and drill exercises currently employed by swimmers to investigate which of these exercises develop and implement the correct muscular activation pattern and which exercises encourage an incorrect pattern. 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 muscular recruitment pattern for swimming breaststroke at the highest level.

In addition, watching the final of the Olympic Games or the World Championship, there are noticeable differences in swimming technique between athletes. Therefore, individual differences in swimming technique due to factors such as different anthropometry, strength, flexibility, endurance and work economy should also be considered when using EMG and kinematic analyses for evaluating and coaching breaststroke swimming. Thus, coaches should prioritize individual instead of group feedback.

Finally, this thesis also revealed that though the muscle activation patterns do not significantly change between maximal and submaximal effort, there are changes in terms of muscular amplitude and activation time. This should be taken into account when exercising at lower intensities and exercising to stimulate specific muscles and movement patterns for optimal performance during a competition.

7 Conclusion

In conclusion, the present *Studies* demonstrated:

Study 1

This study confirmed the hypothesis that the EMG amplitude would be the same before and after 90 min of submersion (including 60 min of easy swimming) using minimal measures for waterproofing the electrodes, and between land and water measurements using the proposed electrode configuration and procedures. The use of this method can therefore be considered a reliable assessment for muscle activation during prolonged submersion without the need for additional waterproofing and may be used not only for measuring elite and novice swimmers, but also for conducting experiments in other aquatic sports, and for developing exercises for prevention and rehabilitation of injuries and chronic diseases.

Study 2

This study proposes a specific method for identifying the different phases of the leg kick in the contemporary breaststroke technique to encompass the fact that not all elite swimmers have the feet actively coming together during the insweep, followed by a streamlined glide and active knee bend to start the recovery. The four phases in this specific method are therefore: 1) propulsion, from the smallest knee angle during recovery until the first peak in knee angle during propulsion; 2) insweep/body undulation/glide from the end of phase 1 until the second peak in knee angle; 3) first part of the recovery, from the end of phase 2 until a 90 degree knee angle; and 4) second part of the recovery, from the end of phase 3 until the legs return to position 1.

Study 3

This study confirmed the hypothesis that muscular activation would increase with increasing effort while the timing of muscle activation patterns would remain similar.

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

This led to increased velocity with increasing effort due to a significant decrease in the length of the gliding phase combined with a decrease in the time spent in the leg recovery phase. In addition the knee angle at the beginning of the leg kick decreased with increased effort, providing a better mechanical advantage.

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 could be used as a reference for teaching technique.

Study 4

The main muscular activities were observed in the leg kick phase, to perform a powerful lower limb extension. The most skilled swimmer was the only one to solicit his muscles during the gliding phase to actively achieve a better streamlining. Important activation peaks during the leg recovery correspond to the limbs acting against water drag. Such differences in EMG strategies among an elite group highlighted the importance of considering the muscular parameters used to control the intensity of activation among the phases for a more efficient breaststroke kick.

Study 5

This study confirmed the hypothesis that WC+ and WC swimmers show a different and more economical muscle activation pattern than NE swimmers.

The results have provided descriptions of contemporary breaststroke technique from a neuromuscular perspective and showed that a distinct difference in muscle activation pattern exists between swimmers in different performance levels. The best swimmers began their arm pull at the end of the leg kick phase with activation in TB to extend their reach during the outsweep, followed by an early catch with activation in BB while thereafter initiating an early activation in PM for a powerful insweep. In WC swimmers, muscle activation for the legs was characterized as follows: GAS activates towards the end of the leg kick, RF at the beginning of gliding and an earlier activation in BF during leg recovery. WC swimmers also spent significantly less time in the leg kick and leg recovery phases than NEs. In conclusion, the longer coactivation and less economical use of the muscles found in NEs may be related to a greater metabolic cost while swimming, which could be detrimental to performance.

This knowledge can be used not only for improving training efficiency and technique in competitive swimmers, but also for teaching beginners and designing applicable weight training and dry-land programs.

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9 Tables and Figures legends

9.1 Tables:

9.2 Figures:

Study 1 in full text

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.

Journal of Electromyography and Kinesiology 24 (2014) 698–703

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Surface electromyographic measurements on land prior to and after 90 min of submersion (swimming) are highly reliable

Bjørn Harald Olstad [a,*], Christoph Zinner [b], Jan Cabri [a], Per-Ludvik Kjendlie [a]

[a] Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway
[b] Institute of Training Science and Sport Informatics, German Sport University Cologne, Cologne, Germany

ARTICLE INFO

Article history:
Received 16 July 2013
Received in revised form 16 April 2014
Accepted 12 June 2014

Keywords:
Reliability
Electromyography
Methods
MVC
Land
Water
Submersion

ABSTRACT

The purpose of this study was to investigate the reliability of surface electromyography (sEMG) measurements after submersion (swimming) for 90 min. Isometric maximal voluntary contractions (MVC) on land and in water were collected from eight muscles on the right side of the body in 12 healthy participants (6 women and 6 men). Repeated measures analyses of variance (general linear model ANOVA) showed no significant differences in the peak amplitude MVC scores between land pre and post measurements for all muscles, $p > .05$. The mean of the Intraclass correlation coefficient (1,1) for land pre and land post was .985 with (95% CI = .978–.990), for land pre and water pre .976 (95% CI = .964–.984) and for land pre and post, water pre and post .981 (95% CI = .974–.987). Measuring sEMG on land before and after a prolonged submersion is highly reliable without additional waterproofing when using electrodes with 57 mm diameter.

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1. Introduction

Kinesiological electromyography (kEMG) can be used to objectively analyze muscular activity, function, coordination and coactivation in complex dynamic movements such as swimming (Caty et al., 2007; Clarys and Cabri, 1993; Lauer et al., 2013). Surface EMG (sEMG) is the primary method of kEMG studies because of its non-invasiveness. The first authors that used sEMG for underwater measurements on humans during swimming were (Ikai et al., 1961, 1964). In 1967, Lewillie (1967) introduced techniques of telemetered sEMG in water. Good correlations between fine wire and sEMG in underwater recordings were found ten years later (Okamoto and Wolf, 1979). Since then, the use of sEMG in swimming and water exercises has become increasingly popular e.g. (Pinto et al., 2010; Pöyhönen, 2002; Rainoldi et al., 2004).

However, the use of sEMG in water is to some extent quite different from dry land conditions. Masumoto and Mercer (2008) and the work of Veneziano et al. (2006) addressed several methodological considerations and confounding factors for measuring sEMG in the aquatic environment. Veneziano et al. (2006) identified six confounding factors for conducting sEMG in water: (1) implementation of different protocols; (2) water leakage to the electrodes; (3) study of different muscles; (4) buoyancy forces; (5) different degrees of body immersion, from the isolated limb to the whole body; and (6) different water temperature with respect to the skin temperature.

Good reliability between land and water measurements were obtained in the following studies after controlling for certain confounding factors; Pinto et al. (2010) and Veneziano et al. (2006) controlled for water temperature (31–32 °C), Alberton et al. (2008) that the body was fully immersed, and (Abbiss et al., 2006; Alberton et al., 2008; Carvalho et al., 2010; Pinto et al., 2010; Rainoldi et al., 2004; Silvers and Dolny, 2011; Veneziano et al., 2006) that the electrodes were protected and covered with adhesive dressings or tape to avoid water infiltration.

Another important question is whether the sEMG signal is altered due to the stay in water. To our knowledge, Clarys et al. (1985) and Silvers and Dolny (2011) are the only studies that compared water sEMG recordings before and after aquatic exercise. Clarys et al. (1985) compared water sEMG before and after swimming while Silvers and Dolny (2011) compared water sEMG recordings from maximum voluntary contraction (MVC) on dry land, and in water before and after aquatic treadmill running. Neither of these studies investigated land pre and post measurements to aquatic activity and prolonged submersion. Abbiss et al. (2006) is the only study to compare land pre and post measurements. They found no difference between land measurements after a 15 min submersion with waterproofing the electrodes.

* Corresponding author. Address: Norwegian School of Sport Sciences, Department of Physical Performance, Sognsvn. 220, 0863 Oslo, Norway. Tel.: +47 930 61 946.

E-mail address: b.h.olstad@nih.no (B.H. Olstad).

http://dx.doi.org/10.1016/j.jelekin.2014.06.006
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In the literature, only a few muscles have been investigated for reliability between land and water sEMG measurements using MVC (Table 1). Among these muscles biceps brachii (BB), biceps femoris (BF), vastus lateralis (VL) and vastus medialis (VM) showed positive correlations between land and water, but lower amplitude in water than on land.

There are also very few studies comparing the reliability of the power spectrum density (PSD) on land and in water. Veneziano et al. (2006) found no changes in the average root mean square and median frequency values between measurements taken underwater and in air when eliminating their known confounding factors. Petrofsky and Laymon (2005) found a decrease in the median frequency by 32 Hz for water temperatures under 27 °C.

These previous studies indicate that there is still a need for further investigation of the reliability between sEMG amplitude and frequency on land and in water. Moreover, it can still be questioned whether sEMG during prolonged submersion is reliable and reproduces true activation of the muscles under investigation. Therefore, the main objective of the present study was to investigate the reliability of sEMG on land before and after 90 min of submersion (including 60 min of easy swimming) using minimal measures for waterproofing the electrodes. Additionally, the study aimed to compare sEMG of MVCs on dry-land and in water from muscles which are of high relevance for technical studies in swimming.

2. Methods

2.1. Participants

Twelve healthy students from the Norwegian School of Sport Sciences, 6 women (mean age: 23.3 ± 2.6 years; range: 21–28 years, height: 168.5 ± 6.0 cm and body mass: 61.6 ± 8.3 kg) and 6 men (mean age: 23.3 ± 2.0 years; range: 20–25 years, height: 185 ± 5.8 cm and body mass: 82.2 ± 7.4 kg), volunteered to participate in this study. All participants were good to excellent swimmers and were able to swim at least 60 min as part of their regular training. They all signed an informed consent approved by the national ethics committee, in accordance with the Declaration of Helsinki and were asked to avoid vigorous exercise in the last 24 h before the experiments.

2.2. Familiarization

All participants completed a familiarization session 5 ± 1.1 days before the main testing. The familiarization session included skin preparation, marking of the electrode sites on the body and on transparent plastic covers and performance of three MVC's on land with instructions for all eight exercises (muscles).

Table 1
Studies showing good reliability between land and water surface electromyographic measurements with waterproofing the electrodes (X) and lower measurements in water than on land (O).

Authors	Year	ABP	BB	BF	GAS	RF	TA	TB	VL	VM
Abbiss et al.	2006								X	
Alberton et al.	2008								X	
Carvalho et al.	2010		X							
Clarys et al.	1985		O							
Kalpakcioglu et al.	2009		O							
Pinto et al.	2010		X	X		X		X		
Pöyhönen et al.	1999			O					O	O
Rainoldi et al.	2004		X							
Silvers & Dolny	2011			X	X	X	X			X
Veneziano et al.	2011	X								

ABP = abductor pollicis brevis, BB = biceps brachial, BF = biceps femoris, GAS = gastrocnemius medialis, RF = rectus femoris, TA = tibialis anterior, TB = triceps brachial, VL = vastus lateralis, VM = vastus medialis.

2.3. Electrode preparation and placement

To minimize 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 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 Ltda, Lisbon, Portugal) were positioned at the midpoint of the contracted muscle belly (Clarys and Cabri, 1993; in line with the direction of the muscle fibers according to the European recommendations for surface electromyography (Hermens et al., 1999, 2000)). Two self-adhesive foams (Multi Bio Sensors Inc., 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 subjectś skin. This special construction provided a waterproof seal with the snap connector. The amplifier was embedded in silicon material to sustain waterproof (Fig. 1). A ground electrode was placed on the os frontalis.

The electrode holders were covered with insulating tape around the outside perimeter for protection against the water flow during swimming. Insulating tape was also used for fixing the cables to the body for limiting movement artifacts (Rainoldi et al., 2004). No additional waterproofing of the electrodes, snap connectors or cables was performed (Fig. 2). The cables from the electrodes on the leg were routed along the lateral aspect of the right leg, through the swimming suit and along the medial back to the waterproof pouch connected to the participants swim cap (Fig. 3). From the upper body the cables were routed to the medial side of the back and into the waterproof pouch.

2.4. Experimental design, MVC testing

Eight muscles of the right side of the body were selected for this study: Biceps Brachii (BB), Triceps Brachii (TB), Trapezius (TRA), Pectoralis Major (PM), Rectus Femoris (RF), Biceps Femoris (BF), Tibialis Anterior (TA) and medial head of Gastrocnemius (GAS).

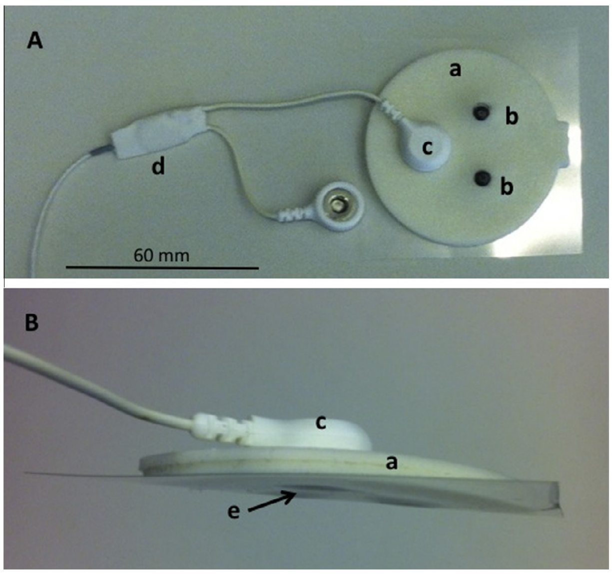

Fig. 1. Configuration of the EMG sensors (A) top view; (B) side view. Legend: (a) adhesive electrode holder; (b) sensor connector for clip; (c) connector clip (snap connector); (d) EMG amplifier; and (e) Ag/AgCl pre-gelled sensor (in contact with skin).

Isometric MVC testing was used to verify the reliability of the sEMG signal on land and underwater before and after 90 min of submersion (including 60 min of relaxed swimming performed as 25 m intervals with technique exercises). Testing and data collection was conducted on the pool deck and in the 12½ and 25 m indoor pool at the Norwegian School of Sport Sciences with air and water temperature between 29 and 30 °C. For each muscle, the participants were instructed to exert a maximal isometric force and hold it for 5 s, separated by about 45 s of recovery in standardized exercises (Table 2). Each contraction was repeated three times. Strong verbal encouragement was provided during all tests to help participants' maximal effort. Each set of MVC tests on land and in the water were performed in identical order and during the MVC testing in water electrodes were fully submerged. The testing protocol for all participants is described in Fig. 4.

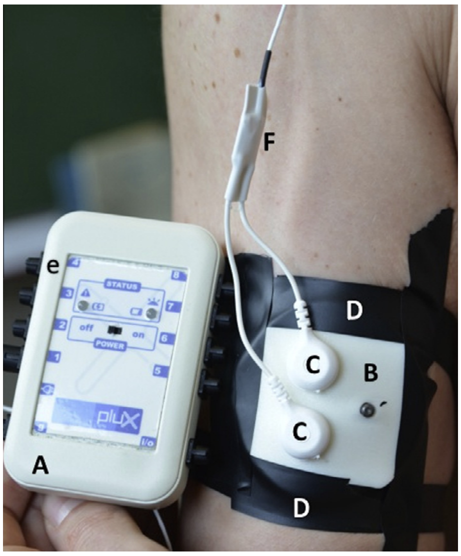

Fig. 2. The electrode, connectors, amplifier, and wires. Legend: (A) input box with Bluetooth transmitter; (B) adhesive electrode holder; (C) snap connector; (D) insulating tape; (e) EMG input channel; and (F) EMG amplifier.

Fig. 3. The waterproof pouch. Legend: (A) waterproof pouch; (B) input box; (C) data logger; and (D) cables (coming from the EMG sensors).

The standardized exercises in Table 2 were designed so that they could easily be performed in a field setting on the pool deck and in the swimming pool with no stationary machines. One of the confounding factors of Veneziano et al. (2006) was the buoyancy forces in the water. To limit the buoyancy factor, all measurements in the water were taken with electrodes only being immersed at 10–40 cm and weights were either placed on the subject's legs to keep them from floating up or their shoulders were pushed and held under water.

2.5. Data acquisition and processing

All procedures for acquiring, processing and analyzing the sEMG signals were performed according to the recommendations from the International Society of Electrophysiology and Kinesiology (Merletti, 1999; Merletti et al., 2009). The Ag/AgCl sEMG electrodes, fixed to the adhesive electrode holders (Fig. 2) were connected to waterproof sEMG active dipole sensors (pre-amplifiers) through the snap-on connectors from Plux Ltda, Lisbon, Portugal with a band pass filter of 25–500 Hz (−6 dB), input impedance > 100 MΩ, common mode rejection ratio was 110 dB and was amplified with a gain of 1000. The sensors were connected to the bioPlux Research Input Box (Plux Ltda, Lisbon, Portugal) with dimensions of 84 · 53 · 18 mm and weight 86 g inside a waterproof pouch with 8 analogue channels (12 bit), sampled at 1000 Hz and with a measuring range of 5 mV (Fig. 3). The signals were telemetrically recorded through a Bluetooth high range adapter and visually inspected while recording in real time with the MonitorPlux v2.0 software (Plux Ltda, Lisbon, Portugal). Before conducting the MVC's, a resting sEMG together with a dynamic contraction was obtained for checking the quality of the sEMG signal.

Python v2.6.7 (Python Software Foundation, Delaware, USA) was used for signal analysis. Raw sEMG signals were full-wave rectified and smoothed using a low-pass FIR filter with a cutoff frequency of 500 Hz. The peak sEMG amplitude was calculated with 200 ms RMS and the highest amplitude peak for all trials was selected for further analysis (Abbiss et al., 2006; Hermens et al., 1999). The power spectrum of the signal (mean average frequency and peak frequency) was analyzed using 2048-point Fast Fourier Transform (FFT).

2.6. Statistical analysis

SPSS v18.0 (SPSS Inc, Chicago, USA) and Microsoft Excel (Microsoft Corp., Washington, USA) were used for all statistical computations between the measurements. The maximum amplitude from the three MVC's for each muscle and each testing

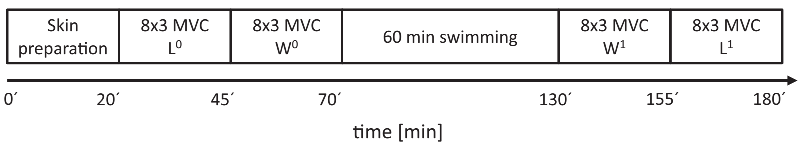

Fig. 4. Testing protocol.

Table 2
Description of the exercises used for MVC testing on each of the eight muscles.

Muscle	Procedure
Biceps brachii	Sitting next to a stair. The right elbow was resting on the stair and the right hand grabbed onto a strap. The length of the strap was fixed to reach an elbow angle of 90°, shoulder flexion were 0° and shoulder abduction 30°. The participant pulled the strap towards the chest
Triceps brachii	Sitting next to a stair. The right hand grabbed onto a strap. The length of the strap was fixed to reach an elbow angle of 90°. Shoulder flexion and abduction was 0° and the participant pressed straight downwards on the strap
Trapezius (pars descendens)	Standing position. Right shoulder was pressing up against a strap which was fixed underneath the foot of the participants and over the right lateral clavicula. Investigators paid attention that participants elevated their acromial end of the clavicula and scapula
Pectoralis major (pars clavicularis)	Standing in front of a ladder. Both underarms touched the ladder with a 90° angle in the elbows and shoulders. The ladder was a little wider than the shoulders and the participants pressed against the ladder
Rectus femoris	Sitting upright (on a chair) with a strap fixed at the ankle. Participants tried to extend the knee without rotating the thigh while applying pressure against the leg above the ankle in the direction of flexion. The angle of the knee and hip were kept constant at 90°
Biceps femoris	Lying submersed on a platform in a prone position with a strap fixed at the ankle. The length of the strap was fixed to a knee angle of 135°. The hip angle was 0°
Tibialis anterior	The first six participants sat on a stair with a strap around the bottom of their toes and the ankle in a 90° angel. The participants were instructed to keep the heel on the ground and push their feet towards them The last six participants supported the leg just above the ankle joint with the ankle joint in dorsiflexion and the foot in inversion without extension of the great toe. Pressure were applied against the medial side, dorsal surface of the foot in the direction of plantar flexion of the ankle joint and eversion of the foot
Gastrocnemius	The first six participants sat on a stair with a strap around the bottom of their toes and the ankle in a 90° angel. The participants were instructed to keep the heel on the ground and push their feet away from them. The last six participants had the foot in plantar flexion with an emphasis on pulling the heel upward instead of pushing the forefoot downwards. For maximum pressure in this position it was necessary to apply pressure against the forefoot as well as against the calcaneus

condition was adopted for statistical analysis. Shapiro–Wilk was used to check for data normality. Repeated measures analyses of variance (general linear model ANOVA) were performed to test overall differences in MVC peak amplitude between exercise conditions for parametric variables. Friedman's ANOVA was used for variables which were not normally distributed. Typical error, represented by the coefficient of variation (CV%) was calculated to provide an indication of the intra-subject variability between pre and post water submersion for each muscle. Cronbach's test of reliability was carried out on the MVC signal on land pre and post to evaluate the reproducibility of the MVC scores. Intraclass correlation coefficient (ICC) (1,1) was carried out for the experimental conditions (land and water, pre and post) within each muscle using a one way random effects model. ICC greater than 0.80, was considered to represent high reliability (Abbiss et al., 2006; Netto and Burnett, 2006).

3. Results

The testing procedure for submersion in water for 60–90 min showed high reliability and integrity of the sEMG recordings. There were no significant differences in peak amplitude MVC scores between land pre and post measurements for all muscles. Since sphericity of the data could not be assumed (Mauchley's test of sphericity) a Greenhouse-Geisser correction was used for the degrees of freedom based on the epsilon value of $\varepsilon < .75$. The test showed no difference between sEMG conducted on land pre and post for BB, TA, BF and RF, $F(2,19) = 1.03$, $p > .05$ or for land and water pre and post $F(1,12) = 1.38$, $p > .05$. Friedman's ANOVA showed no difference between sEMG conducted on land pre and post for TB, TRA, PM and GAS, $x^2(1) = 0.21$, $p > .05$ or for land and water pre and post $x^2(3) = .24$, $p > .05$.

Average CV% for all muscles before and after water submersion was 10% and 11% for land pre and water pre testing (Table 3). The ICC between land pre and land post and land pre and water pre showed very strong positive correlations for 15 groups and strong positive correlation for 1 group, (Table 4). All pairs had 95% Cl including 0.

The Cronbach's alpha coefficient was .985 between land pre and land post, .979 between land pre and water pre .979, and .982 between all four conditions.

The mean of the ICC (1,1) for land pre and land post was .985 (95% Cl = .978–.990), for land pre and water pre .976 (95% Cl = .964–.984) and for all four testing conditions was .981 (95% Cl = .974–.987).

Mean average frequency on land was 138 Hz (SD 28.04) and in water 134 Hz (SD 31.11). Peak average frequency on land was 69 Hz (SD 24.16) and in water 61 Hz (SD 29.21). A paired sampled *t*-test showed no significant differences either for the mean frequency ($p = 0.31$) nor for the peak frequency ($p = 0.09$).

4. Discussion

The results of the present study indicate high reliability of the sEMG recordings on land before and after 60 min of easy swimming and for a total of 90 min water submersion. The ICC test values also indicated that all variables can be considered reproducible both in water and on dry-land.

After inspecting the video recordings from the first 6 participants it was sometimes observed that the aimed joint angle of 90° of the talo-crural joint were not constant for GAS and TA throughout all trials. Sometimes the strap gave the participants a little range of motion and therefore the exercise was modified for the last 6 participants.

Some studies have compared MVC's on land and in water with different results for sEMG amplitude (Table 1), but no previous study has tried to measure the reliability on land before and after a sustained submersion with water activity in between. Only two studies compared land and water sEMG in conjunction with water activity. Clarys et al. (1985) found significantly lower sEMG recordings from both the telemetry and tethered sEMG systems for the BB in water compared to land measurements after crawl swimming. Silvers and Dolny (2011) did not measure MVCs on land before and after aquatic treadmill running, but however found no significant difference between sEMG recordings from MVC's on land, in the water after running, and again in the water after running with waterproofing the electrodes and connectors. Abbiss et al. (2006) are the only known authors to compare sEMG on land before and after a water submersion, but without water activity in between. As in the present study, they found no difference between land measurements taken before and after 15 min of submersion, but with waterproofing the electrodes.

Veneziano et al. (2006) identified buoyancy as a factor that can reduce the actual force produced in water compared to measuring in air. Several other studies have reported on this, also (Clarys et al., 1985; Fujisawa et al., 1998; Kalpakcioglu et al., 2009; Pöyhönen

Table 3
Root mean square of the maximum peak from the three trials of isometric MVC (μV).

Muscle	Testing condition	Mean	SD	CV%
Biceps brachii	Land pre–post	593.09	35.52	7
	Land pre–water pre	554.95	51.90	11
Triceps brachii	Land pre–post	249.63	23.72	12
	Land pre–water pre	254.26	19.94	9
Trapezius (pars descendens)	Land pre–post	546.71	61.88	13
	Land pre–water pre	494.25	70.99	16
Pectoralis major (pars clavicularis)	Land pre–post	196.59	17.93	10
	Land pre–water pre	189.78	24.03	14
Rectus femoris	Land pre–post	176.10	44.82	11
	Land pre–water pre	186.96	25.39	14
Biceps femoris	Land pre–post	177.29	14.78	9
	Land pre–water pre	186.96	25.39	14
Tibialis anterior	Land pre–post	217.86	36.82	18
	Land pre–water pre	221.97	13.74	6
Gastrocnemius	Land pre–post	113.37	12.24	12
	Land pre–water pre	105.05	18.61	15
Mean	Land pre–post	282.43	28.18	10
	Land pre–water pre	271.47	30.68	11

Values expressed as mean, Standard deviation (SD) and Coefficient of Variation (CV).

Table 4
Intra class correlation coefficient for testing conditions.

Pair	Correlation
Biceps brachii land pre & post	.981
Pectoralis major (pars clavicularis) land pre & post	.974
Triceps brachii land pre & water pre	.972
Triceps brachii land pre & post	.957
Biceps brachii land pre & water pre	.954
Gastrocnemius land pre & post (6 participants)	.953
Tibialis anterior land pre & water pre (6 participants)	.937
Pectoralis major (pars clavicularis) land pre & water pre	.928
Biceps femoris land pre & post	.914
Tibialis anterior land pre & post (6 participants)	.908
Trapezius (pars descendens) land pre & post	.891
Biceps femoris land pre & water pre	.867
Trapezius (pars descendens) land pre & water pre	.818
Gastrocnemius land pre & water pre (6 participants)	.805
Rectus femoris land pre & water pre	.801
Rectus femoris land pre & post	.725

et al., 1999; Sugajima et al., 1996), and found that the reduction in sEMG signal in water might be triggered by impairment of the neuromuscular system. This may be caused by the reduction in individual's weight and by the hydrostatic pressure that acts upon the body during immersion which may alter sensitive input. Rainoldi et al. (2004) and Veneziano et al. (2006) measured only the limb that was immersed in water while Pinto et al. (2010) measured sEMG with the body submerged, all studies showing good reliability. As in the studies of Pinto et al., 2010; Rainoldi et al., 2004; and Veneziano et al., 2006 the present study tried to eliminate the buoyancy factor by ensuring that the muscles tested were submerged in shallow depths (10–40 cm).

Differences in water and air temperature can further increase the heat transfer in water and lead to lower sEMG signal detection (Veneziano et al., 2006). Petrofsky and Laymon (2005) found a significant decrease from land MVC amplitude after submersion in water temperature at 24 °C of up to 44.8%, but not within temperatures from 27 to 34 °C. The present study eliminated the differences in water and air temperature by ensuring 29–30 °C both on land and in the water.

Rainoldi et al. (2004) showed that submersion in pool water without waterproofing the electrodes and free electrode cables resulted in a decrease in sEMG amplitude during submaximal isometric contractions (50% of MVC) of 6.7% compared to dry conditions for the BB. The power spectrum was also altered by water movement compared to motionless water. The increase of spectral power in the frequency range of 0–20 Hz resulted in a decrease in the median frequency. Pöyhönen et al. (1999) tested VM, VL and BF in seated maximal and submaximal isometric contractions in water and on land three times over two weeks. They found lower sEMG muscle activity in water for all muscles, VM and VL a decrease in amplitude of 11–17% and for BF about 17–25%. Pöyhönen and Avela (2002) tested the muscle activity of soleus (SOL) and GAS medialis through an MVC ankle plantar flexion both on land and in water. The results showed a decrease in sEMG by 7.9% for SOL and 13.6% for GAS. In the present study we took into consideration the known effects: cable artifacts by fixing them with extra adhesive tape on the limbs, loosening of the electrodes from the skin by increasing the adhesive surface in contact with the skin and reinforcement using adhesive tape. Carvalho et al. (2010) found that the covering tape used on a dry surface does not affect the sEMG amplitude on land, but without its usage it can reduce signal amplitude in the water by nearly 50%. Veneziano et al. (2006) also suggested that covering tape in the water and on dry-land develops a certain mechanical pressure on the skin and the muscle tissue under the electrode. In accordance with the studies mentioned, we used insulating tape to fix the perimeter of each electrode including the electrode connectors and the loose cables along the subjectś body to limit movement artifacts ensuring a mechanical pressure on the skin and the muscle tissue under the electrode and to avoid movements detaching the electrode from the participants body.

Another aspect of sEMG testing on land and in water that has not previously been addressed in the literature is the size of the electrodes. In all of the mentioned studies there is either an uncertainty about which electrode size was (ref) or the reported inter-electrode distance varied between 10 mm and 19 mm. All studies used bipolar electrodes. In terms of increasing the mechanical pressure on the skin and the muscle tissue under the electrode we used waterproof self-adhesive material with a diameter of 57 mm in which the sensors (electrodes) were embedded. Furthermore, taping the perimeter around the electrodes with insulating tape was an additional method to prevent water from infiltrating to the sensors. Our findings contradict some findings of the literature (Abbiss et al., 2006; Carvalho et al., 2010; Rainoldi et al., 2004; Silvers and Dolny, 2011; Veneziano et al., 2006) who advise to put an extra water-resistant protection on the electrodes while using them in water. As long as buoyancy, temperature, cable connections and loose cables are accounted for, using large waterproof electrodes with taping the perimeter is in our opinion sufficient to sustain water infiltration.

5. Conclusion

This study identified that sEMG measurements using the proposed electrode configuration are reliable even after 60–90 min of water submersion (relaxed swimming). The use of this method can therefore be considered a reliable assessment for muscle activation during prolonged water activity without the need for extra waterproofing which may restrict the participant's range of motion.

Conflict of interest

None.

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Bjørn Harald Olstad, born in Oslo (Norway) is an assistant professor at the Norwegian School of Sport Sciences in Oslo with the Department of Physical Performance. He is currently working towards his PhD: "Muscle activation and kinematics in contemporary breaststroke swimming", containing surface electromyographic measurements and 3D motion analyses in swimming. He holds a master's degree on how to coach age-group swimmers for future success and was a former National team member in swimming and lifesaving. He previously worked for the United States Olympic Committee, United States Swimming and with several swim clubs as performance director and coach.

Christoph Zinner received his PhD in Sport Science at the German Sport University Cologne in 2013. Actually, he is a post-doctoral researcher at the Swedish Wintersport Research Center in Östersund, Sweden. His scientific interests are in the field of training science and the influence of modulation of external stimuli on physical performance of athletes.

Jan Cabri, born in Brussels (Belgium), received his PhD in Physical Therapy and Motor Rehabilitation in 1989 at the Vrije Universiteit Brussel. He was awarded an associate professorship in Sports Medicine at the Faculty of Medicine of the aforementioned university in 1992. From 1996 to 2009 he was invited as a visiting professor at the Technical University Lisbon, Faculty of Human Movement (Portugal), after which he was appointed as Professor and Head of the Department of Physical Performance, at the Norwegian University of Sport and Physical Education (Norway). His research interests are mainly in applied (sports) biomechanics and kinesiologic electromyography. He is a member of the Scientific Board of the European College of Sports Science and of the World Commission of Sport Science, Science and Football Steering Group. Furthermore, he serves as Section editor in the European Journal of Sport Science.

Per-Ludvik Kjendlie (42) has been a swimming instructor and coach since the age of 15. His experience spans from the club to national team level, and has spent several years as a National Junior team head coach and handicapped national team technique coach. After working as the technical director of the Norwegian Swimming Federation, he started an academic career at the Norwegian School of Sport Sciences with master and PhD studies in swimming, physiology and biomechanics. The PhD title was "The swimming Child: Working Economy" (2004). A strong research interest has been the physiological differences between children and adults in swimming, problems of scaling performance parameters in swimming for size, and performance determining factors of anthropometry, biomechanics and physiology in swimming. Per-Ludvik Kjendlie was a co-chairman of the 11th International symposium for Biomechanics and Medicine in Swimming, Oslo 2010.

Study 2 in full text

Olstad, B.H., Zinner, C., Haakonsen, D., Cabri, J., & Kjendlie, P.L. (2014).

A new approach for identifying phases of the breaststroke wave kick and calculation of feet slip using 3D automatic motion tracking.

In B. Mason (Ed.), *Proceedings of the XIIth International Symposium on Biomechanics and Medicine in Swimming 28 April to 2 May 2014* (pp. 195-199). Canberra, AUS: Australian Institute of Sport.

A new approach for identifying phases of the breaststroke wave kick and calculation of feet slip using 3D automatic motion tracking

Bjørn Harald Olstad[1], Christoph Zinner[2], David Haakonsen[1], Jan Cabri[1], and Per-Ludvik Kjendlie[1]
[1]Department of Physical Performance, Norwegian School of Sport Sciences, Norway, [2]Institute of Training Science and Sport Informatics, German Sport University Cologne, Germany

Keywords: swimming, breaststroke, kick, phases, biomechanics, 3D automatic motion tracking

Abstract

This study proposes a new method for identifying the different phases of the leg kick in the modern breaststroke technique. Previous analysis models assume that all breaststroke kicks finish with feet actively coming together during the insweep followed by a 'flat glide' and active knee bend to start the recovery. Using the previous models for the swimmers tested the phases could not be accurately separated due to the different wave amplitudes in their technique influencing their insweep and knee bend timing during recovery. Four phases of the breaststroke kick were therefore identified using 3D automatic motion tracking: 1) propulsion, from the smallest knee angle during recovery of the legs until the first peak in knee angle during propulsion, 2) insweep/wave motion/glide, from end of phase 1 until second peak in knee angle, 3) first part of the recovery, from end of phase 2 until 90 degree knee angle and 4) second part of recovery, from end of phase 3 until legs reach position 1. The method uses distinct positions of the 3D markers, their trajectory and peak angles to give a better understanding of the phases in the modern breaststroke technique as well as accounting for different styles of breaststroke technique.

Introduction

The Fédération Internationale de Natation (FINA) rule change on February 15th 1987 allowed the swimmers to break the water surface during arm recovery and dive below the water surface with their head during a breaststroke cycle (Colman et al. 1998). This started the evolution of the wave/dolphin style breaststroke technique, used today by almost every competitive breaststroker. Dividing the arm stroke and leg kick into phases has offered researchers to study the motor patterns and interlimb coordination during the different swimming strokes. The first studies in swimming looking at motor patterns came from Vaday et al. (1971) in front crawl and Nemessuri et al. (1971) in breaststroke. Since then, several authors have studied motor patterns and interlimb coordination in breaststroke (e.g. Chollet et al. 1999; Chollet et al. 2004; Costill et al. 1992; Leblanc et al. 2009; Sanders 1996; Seifert et al. 2005; Seifert et al. 2006; Seifert et al. 2009; Seifert et al. 2010; Seifert et al. 2011; Soares et al. 1999). These authors analyzed the spatial-temporal relationships between the key points defining the start and the end of each arm and leg stroke phase. Four distinct breaststroke techniques have been identified: vertical, flat, undulating and undulating with arm recovery over the water, which lead to difficulties of finding an ideal mode for arm and leg coordination (Maglischo 1993; Persyn et al. 1992; Tourny et al. 1992; Vilas-Boas et al. 1994; Vilas-Boas 1996). A recent method to analyze breaststroke was developed by Chollet et al. (2004), who identified five phases for both arms and legs and measured the time gaps between the phases using a speedometer-video. These five phases of the breaststroke leg kick are identified as: leg propulsion, leg insweep, leg glide, first part of the recovery until a thigh/leg angle of 90° and second part of the recovery. Chollet et al. (2004) and Seifert et al. (2005) applied this method to analyze the flat style breaststroke and proposed a new index for the arm- and leg coordination in elite and recreational swimmers. Today, there is no specific index for the wave breaststroke or one that encounters all the different breaststroke styles. The purpose of this study was to investigate a new way of identifying and measuring the phases during the breaststroke wave kick and the slip of the foot allowing for a more careful study of technical aspects in each phase using 3D automatic motion tracking.

Methods

Participants

Three international top level swimmers (two male World champions' and one female Olympic medalist) (27.3 ± 1.7 years; 188 ± 2.83 cm; 86.55± 0.78 kg) and 1 female (28.3 years; 168 cm; 73.3 kg) participated in this study. All participants signed informed consent approved by the Norwegian national ethics committee and volunteered to participate in this study.

Motion capture system

A 3D underwater motion capture system (Qualisys, Gothenburg, Sweden) consisting of Oqus 3 and 4 cameras were installed in the pool to record underwater movements for kinematic analysis. The cameras used a high-powered led light with a cyan visible strobe (wavelength of 505nm). To counter the fact that water absorbs light at a much higher degree than air, the underwater cameras were equipped with a very powerful strobe consisting of 12 high power LEDs. The powerful LED solution provided good illumination for 12.5m in clear water and facilitated measurements even with a certain degree of particles in the water. Each LED was also equipped with a lens which focuses the light to approximately a 40 degree wide beam. By angling the LEDs individually an even light pattern was produced over the entire field-of-view (FOV) of the cameras. All cameras were placed inside a waterproof case IP68 and IP69K (Qualisys, Gothenburg, Sweden). Each camera had an active filtering hardware, which greatly reduced unwanted reflections from bubbles and other objects under water. Each camera was also masked for sunlight reflections. The specialised underwater cameras were connected to a power supply, synchronised, and attached to a PC using an Ethernet connection. Qualisys Track manager 2.6 (Qualisys, Gothenburg, Sweden) was used for running the camera setup and capture. The cameras were operating at 100 Hz capturing special retro reflective markers on the swimmers body. Camera set-up consisted of 10 underwater cameras, 5 on each side of the pool, 6 were mounted just below the water surface and 4 were standing on tripods under water (Fig. 1).

Figure 1 Underwater cameras

Markers

The retro reflective material used on normal land markers completely loses reflectivity under water. Therefore, spherical markers of special material suitable for underwater usage were produced by Qualisys (Gothenburg, Sweden). The markers were passive spheres and half spheres with a diameter of 19 mm and where all equipped with a thread for fastening and neutral buoyancy (Fig. 2). They were placed on the swimmers cresta ilíaca, trochanter major, distal part of vastus lateralis (glued to the swimmers suit), lateral femoral condyle, peroneus longus, the most posterior part of the calcaneus, medial and lateral malleolus and metatarsals 1 and 5.

Calibration

Calibration of the 3D motion capture system was performed with an L-frame and a moving wand method (Nedergaard et al. 2013) with two markers fixed with inter-point distance of 749.5 mm following the recommendations of the manufacturer (Qualisys AB 2011). The wand was manually moved through the calibration volume following the path of the swimmers for 300 sec to cover as many points as possible, at least 800-1000 per camera. During this process the 'extended calibration' option was active because all cameras were not able to view the L-frame, which was placed in the middle of the volume on the bottom of the pool. The standard deviation of the wand markers distance during calibration was 1.6 mm. The cameras covered a volume of approximately 37.5 m^3, 10 m (x) x 1. 5m (y) x 2.5 m (z) and is presented in Fig. 3.

Figure 2 **3D marker**

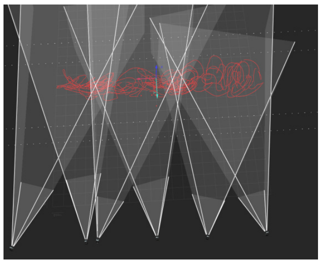
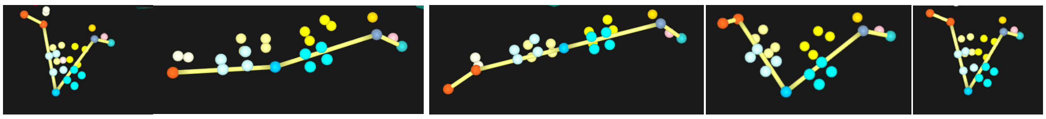


Figure 3 **The calibrated volume under water**

Testing and kinematical analysis

After a personalised warm-up with the equipment, consisting of 15 min of low- to moderate-intensity aerobic swimming with elements of kicking and drills, the swimmers swam all exercises in the same order. Borg´s Rate of Perceived Exertion (RPE) was used to verify the swimmers effort (Borg 1998). The swimmers performed five trials of 20 m normal breaststroke at 60-70-80-90-100% of maximal effort and the 100% trial were analyzed. The second and third last stroke cycles were selected to avoid influence of approaching the wall on the last stroke. The leg kick was divided into 4 phases: 1) propulsion, from the smallest knee angle during recovery of the legs until the first peak in knee angle during propulsion, 2) insweep/wave motion/glide from end of phase 1 until second peak in knee angle, 3) first part of the recovery, from end of phase 2 until a 90 degree knee angle and 4) second part of recovery, from end of phase 3 until legs are back in position 1. The slip of the feet was calculated from the starting point of phase 1 until the x-direction of the ankle marker went from moving backwards to moving forward. An example of a 3D model of the leg kick with automatic tracking is presented in Fig. 4.

a) b) c) d) e)



(a) beginning of phase 1, (b) beginning of phase 2, (c) beginning of phase 3, (d) beginning of phase 4, (e) end of phase 4. Color coding of the markers on the bone structure from left to right: ● calcaneus and metatarsals, ● lateral femoral condyle, ● trochanter major and ● cresta ilíaca.

Figure 4 **Underwater breaststroke kick with 3D automatic tracking**

Results

The four phases of the breaststroke kick during 100% maximal effort and the slip of the feet are shown in Table 1. Swimmer #3 with the most distinct wave breaststroke also showed a much larger knee angle in the beginning and at the end of phase 1 as well as a smaller knee angle in phase 2 and 3. The slip was similar across the subjects, ranging from 300-320 mm.

Table 1 **Times (sec), % of time, knee angles (°) and slips (mm) are shown for the five phases of the breaststroke kick coordination**

	#1				#2				#3			
	P.1	**P.2**	**P.3**	**P.4**	**P.1**	**P.2**	**P.3**	**P.4**	**P.1**	**P.2**	**P.3**	**P.4**
Relative time in phase (s)	.24	.50	.43	.13	.28	.74	.36	.19	.22	.79	.44	.10
% of time spent in each phase	18	38	33	10	18	47	23	12	14	51	28	6
Knee angle (°) During phase	48-165	165-178.5	178,5-90	90-46	43-163	163-172.5	172.5-90	90-44	64-172,5	172.5-168	168-90	90-65
Slip (mm)	313				320				300			

#1, 2, 3 refers to the subjects. P.1, 2, 3, 4 refers to the four different phases of the breaststroke kick

Discussion

This study identified a new model for analyzing the different phases of the breaststroke kick in order to account for the different technique styles used by competitive swimmers. In the past, several models to investigate motor patterns, interlimb coordination and intra-cyclic velocity variations in breaststroke have been presented. These models have a varied number of phases for the arm pull and leg kick. Colman et al. (1992; 1998) digitised 12 images with stick figures to divide the stroke into 8 phases. The newest analysis method from Chollet et al. (2004) divided both the arm pull and leg kick into five separate phases in order to investigate arm-leg coordination in flat breaststroke. The same model has later been used by Leblanc et al. (2005) and Seifert et al. (2005) to evaluate recreational and elite swimmers with the flat breaststroke technique. The challenge with this method for analyzing the breaststroke kick in terms of phases is the assumption that all breaststroke kicks finish with the feet actively coming together during the insweep followed by a 'flat glide' and active knee bend to start the recovery. When applying this method to the swimmers tested in this study, the phases could not be accurately separated due to different wave amplitudes in their technique, influencing both the insweep and knee bend during recovery. Instead of a more traditional up, out, in and glide kick type, these swimmers performed a much more rounded kick which did not always end with the feet being pushed actively together during the insweep. Rather kicking their legs into a wave motion/up-kick was the most observed pattern. The image from Colman et al. (1998) (legs parallel to each other and in line with the hips) would provide a more distinct parameter that could be used for analyses across different technique styles. Chollet et al. (2004) described the first part of the recovery starting with knee flexion and forward movement of the feet. For the subjects tested in this study, knee flexion during the glide as well as forward movement of the feet as a consequence was observed. However, there was still no sign of an active recovery of the legs.

Conclusion

This study proposes a new method for identifying the different phases of the leg kick in the modern breaststroke technique in order to compare swimmers with different techniques. To give a better understanding of the phases, this new method uses distinct positions of markers, their trajectory and peak angles to identify the phases of the modern leg kick.

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Study 3 in full text

Olstad, B.H., Vaz, J.R., Zinner, C., Cabri, J., & Kjendlie, P.L.

Muscle coordination and kinematics in world-class and national-elite breaststrokers at 60-80-100% of maximal effort.

Submitted to *Journal of Sports Sciences.*

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

BJØRN HARALD OLSTAD[1], JOÃO ROCHA VAZ[2], CHRISTOPH ZINNER[3], JAN M. H. CABRI[1] & PER-LUDVIK KJENDLIE[1]

[1]*Department of Physical Performance, Norwegian School of Sport Sciences, Sognsveien 220, 0806 Oslo, Norway,*

[2]*Faculty of Human Kinetics, University of Lisbon, Estrada da Costa, 1499-002 Cruz Quebrada - Dafundo, Lisbon, Portugal and*

[3]*Department of Sport Science, Julius-Maximilians-University Würzburg, Judenbühlweg 11, 97082 Würzburg, Germany*

Corresponding author:

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

Running head: Breaststroke EMG and kinematics

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 (BR) swimming at submaximal and maximal efforts. Surface electromyography (sEMG) was collected from the triceps brachii, biceps brachii, trapezius, pectoralis major, gastrocnemius, tibialis anterior, biceps femoris and rectus femoris 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 BR at 60%, 80% and 100% effort and each SC was divided into three phases; leg kick, gliding and leg recovery. With increasing effort the swimmers decreased their SC length and increased their velocity and stroke rate. A decrease during the different phases was found for: time spent during gliding and leg recovery, distance travelled during gliding and knee angle during the beginning of the leg kick with increasing effort. In addition, 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 SC with increasing effort. Integrated sEMG showed significant increase with increased effort for all muscles except for trapezius during SC. The muscle activation patterns, muscular participation, and kinematics assessed in this study with elite BR swimmers contribute to a better understanding of the stroke, and could be used as a reference for defining good technique.

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 (BR) 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 BR 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 BR and a new style with body undulation was introduced (Van Tilborgh, Willems, and Persyn, 1988) and later Persyn, Colman, and Van Tilborgh (1992) analysed an extremely undulating BR pattern. Technique and mechanics of BR swimming have thus gone through a tremendous change over the past decades from what was called the "flat BR" used by every swimmer, to the modern technique of body undulating BR. Today, this new technique is used by almost every competitive breaststroker with different degrees of undulation.

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 BR increases, stroke length decreases while stroke rate (SR) increases (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 BR 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 BR swimmers.

Methods

Participants

Nine elite BR 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 BR 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 BR paces. Borg's Rate of Perceived Exertion (RPE) was used to verify 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 and 10 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.

A B C D

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

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. 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 length, phase time, 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) leg kick: from the smallest knee angle during recovery until the first peak in knee angle (extension) during the leg kick, (2) gliding: from end of the leg kick to the beginning of active knee flexion for leg recovery, and (3) leg recovery: from end of gliding 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 time, and a significant increase in velocity and SR with increasing effort levels ($p < 0.01$ – Table Ia). The relative phase time and length in % of the complete SC are displayed in Table Ib.

Table Ia. *Time, length 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 gliding phase.*

Kinematic variable	60% effort	80% effort	100% effort	*p*-value
Time for leg kick phase (s)	0.50 ± 0.12	0.46 ± 0.09	0.46 ± 0.07	.130
Time for gliding phase (s)	0.87 ± 0.24	0.70 ± 0.16	0.51 ± 0.14	.000 *abc*
Time for leg recovery phase (s)	0.52 ± 0.09	0.45 ± 0.06	0.41 ± 0.06	.001 *abc*
Length of leg kick phase (m)	0.47 ± 0.07	0.49 ± 0.06	0.48 ± 0.09	.850
Length of gliding phase (m)	1.10 ± 0.21	0.94 ± 0.22	0.82 ± 0.16	.014 *a*
Length of leg recovery phase (m)	0.34 ± 0.07	0.36 ± 0.08	0.40 ± 0.09	.103
Total cycle length (m)	**1.90 ± 0.21**	**1.77 ± 0.22**	**1.70 ± 0.17**	.001 *ab*
Velocity in leg kick phase (m/s)	1.05 ± 0.09	1.15 ± 0.20	1.21 ± 0.20	.015
Velocity in gliding phase (m/s)	1.20 ± 0.17	1.29 ± 0.16	1.33 ± 0.16	.010
Velocity in leg recovery phase (m/s)	0.71 ± 0.10	0.82 ± 0.15	0.97 ± 0.23	.016 *b*
Total cycle velocity (m/s)	**1.04 ± 0.13**	**1.13 ± 0.15**	**1.20 ± 0.16**	.000 *abc*
Stroke rate (strokes/min)	**32.20 ± 3.43**	**38.21 ± 3.27**	**42.58 ± 4.36**	.000 *abc*
Knee angle, beginning of leg kick phase (°)	44.80 ± 2.82	43.49 ± 2.55	42.32 ± 2.56	.025
Knee angle, beginning of gliding phase (°)	168.45 ± 7.71	168.29 ± 7.80	168.31 ± 9.32	.988
Knee angle, beginning of leg recovery phase (°)	157.23 ± 5.42	159.97 ± 7.21	158.19 ± 8.12	.521
Largest knee angle during gliding phase (°)	175.22 ± 2.99	175.34 ± 2.68	175.73 ± 4.09	.876

Note: 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 time and length in % of the complete stroke cycle*.

Kinematic variable	60% effort	80% effort	100% effort	*p*-value
Relative time for leg kick phase (%)	23.71 ± 0.07	27.24 ± 0.07	28.48 ± 0.06	.050
Relative time for gliding phase (%)	50.78 ± 0.18	45.35 ± 0.15	42.19 ± 0.12	.006 *b*
Relative time for leg recovery phase (%)	25.48 ± 0.09	27.43 ± 0.06	29.28 ± 0.06	.002 *b*
Relative length of leg kick phase (%)	24.68 ± 0.07	27.58 ± 0.06	28.49 ± 0.09	.240
Relative length of gliding phase (%)	57.58 ± 0.21	52.33 ± 0.22	47.96 ± 0.16	.028
Relative length of leg recovery phase (%)	17.74 ± 0.07	20.17 ± 0.08	23.55 ± 0.09	.004 *b*

Note: *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%.

The leg kick 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 gliding, knee angle was at its largest. The knee angle stayed relatively constant during this phase, but showed some individual variations until the beginning of leg recovery. A significant decrease in time and length was found during this phase and significant increase in velocity ($p < 0.05$) with increased effort.

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

Distinct individual BR techniques were observed among the swimmers, i.e. the knee angle at the beginning of the leg kick 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 gliding (Figure 3). Some swimmers had knee angle between 179-180° during gliding 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).

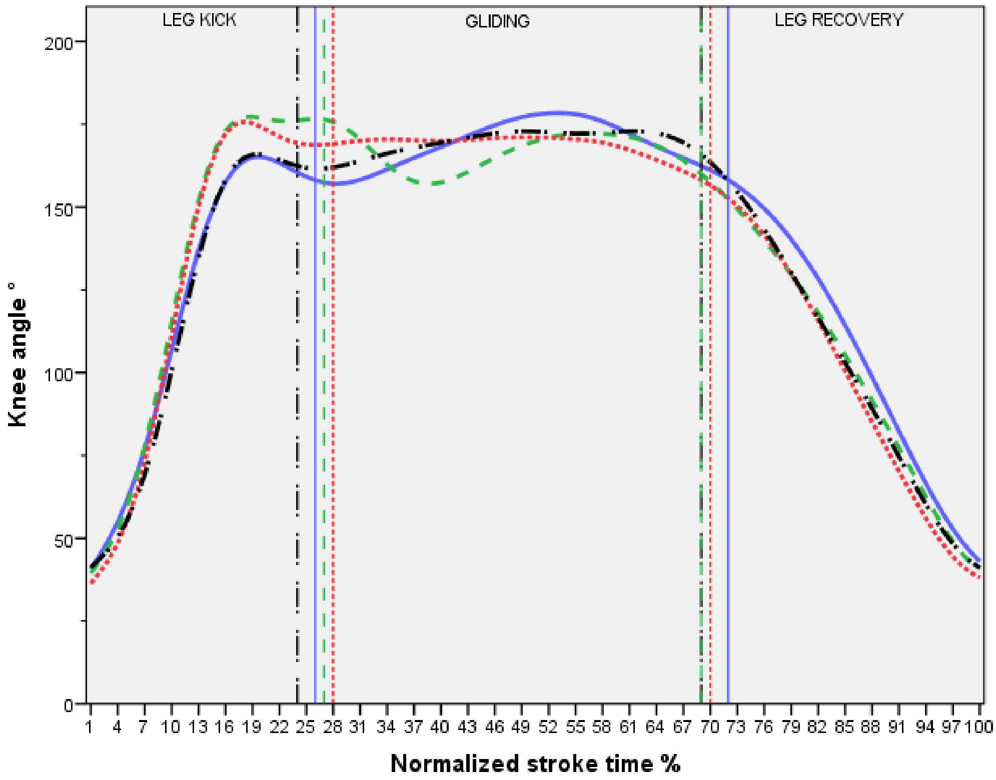

Figure 2. Individual knee angle pattern for four swimmers during the complete stroke cycle for breaststroke swimming at maximal effort. Time is normalised to the stroke cycle (%). —— **swimmer 1**, – – – **swimmer 2**, ····· **swimmer 3** and ·---- · **swimmer 4**.

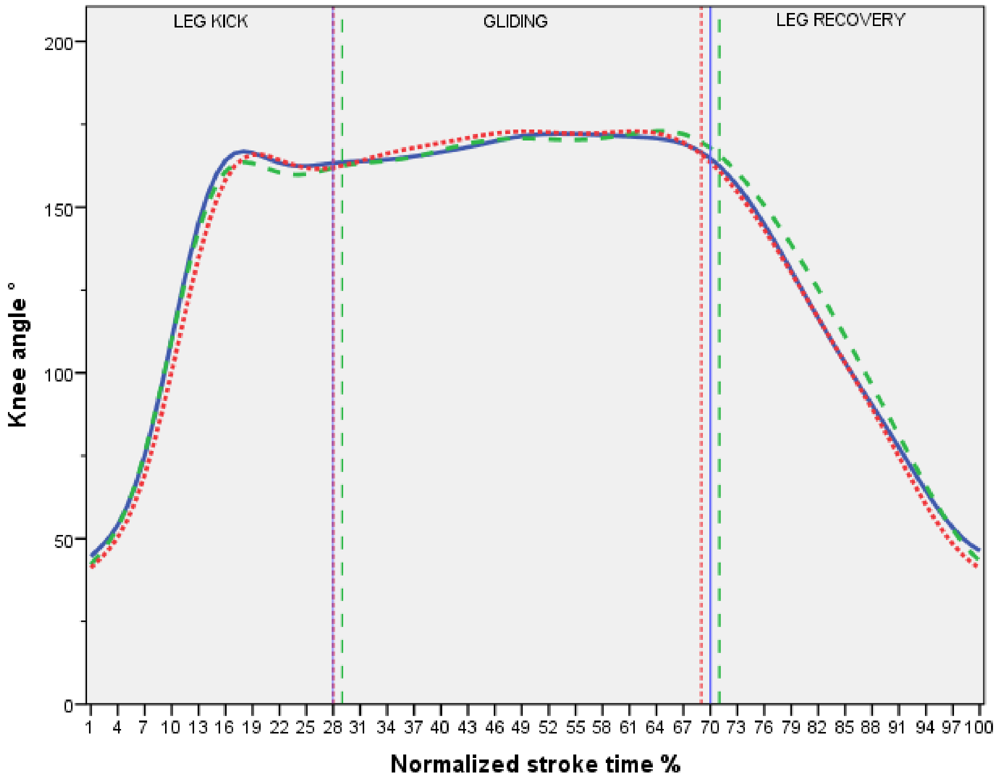

Figure 3. Knee angle pattern during breaststroke swimming at 60-80-100% of maximal effort for one swimmer during the complete stroke cycle. Time is normalised to the stroke cycle (%). —— **60%**, – – – **80%**, ····· **100%**.

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 leg kick and for TB, BB and PM during gliding. TRA showed main activation during the leg kick.

The sum of total iEMG showed significant increase with increasing effort for the entire body (sum of all 8 muscles), $F(2, 16) = 28.06$, $p < .001$, upper body (sum of 4 muscles), $F(2, 16) = 19.08$, $p < .001$, and also for the lower body (sum of 4 muscles), $F(2, 16) = 34.17$, $p < .001$. 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 leg kick 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 leg kick, just before the ankle started going into plantar flexion, a high co-activation between GAS and TA was found.

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)	80% effort iEMG (mV·s)	100% effort iEMG (mV·s)	*p*-value
Leg kick	Triceps brachii	1.32 ± 0.70	1.84 ± .99	3.96 ± 2.67	.000 *abc*
Leg kick	Biceps brachii	1.82 ± 0.97	2.47 ± 1.35	3.05 ± 1.74	.010 *b*
Leg kick	Trapezius	7.28 ± 3.92	9.17 ± 5.09	10.18 ± 4.67	.115
Leg kick	Pectoralis	3.01 ± 3.09	4.45 ± 2.31	4.35 ± 2.63	.008 *b*
Leg kick	Gastrocnemius	5.53 ± 2.96	7.45 ± 3.76	10.1 ± 3.71	.000 *bc*
Leg kick	Tibialis anterior	10.76 ± 5.90	11.94 ± 4.52	15.22 ± 6.31	.020 *bc*
Leg kick	Biceps femoris	5.54 ± 3.16	7.65 ± 4.80	9.68 ± 4.88	.000 *abc*
Leg kick	Rectus femoris	6.87 ± 4.45	7.95 ± 4.35	10.14 ± 5.79	.000 *bc*
Gliding	Triceps brachii	7.68 ± 4.51	9.31 ± 5.78	9.17 ± 5.85	.028 *a*
Gliding	Biceps brachii	6.92 ± 2.27	8.57 ±.3.40	10.51 ± 5.43	.007 *b*
Gliding	Trapezius	4.62 ± 3.07	3.93 ± 2.17	3.17 ± 1.91	.388
Gliding	Pectoralis	7.76 ± 5.35	10.48 ± 6.97	12.14 ± 8.02	.020
Gliding	Gastrocnemius	3.21 ± 3.21	4.72 ± 4.08	5.61 ± 4.89	.015 *a*
Gliding	Tibialis anterior	1.09 ± 0.48	2.56 ± 1.99	2.70 ± 2.13	.011 *a*
Gliding	Biceps femoris	0.91 ± 0.53	1.05 ± 0.43	1.32 ± 0.64	.092
Gliding	Rectus femoris	1.49 ± 0.91	2.00 ± 1.12	2.73 ± 2.03	.007 *b*
Leg recovery	Triceps brachii	3.90 ± 2.95	4.31 ± 3.14	5.05 ± 3.42	.053
Leg recovery	Biceps brachii	6.47 ± 3.87	7.09 ± 4.41	9.31 ± 5.13	.016 *bc*
Leg recovery	Trapezius	4.35 ± 1.67	5.03 ± 2.96	4.90 ± 2.92	.965
Leg recovery	Pectoralis	8.11 ± 5.29	9.96 ± 5.49	10.25 ± 5.59	.028 *b*
Leg recovery	Gastrocnemius	2.02 ± 1.89	2.69 ± 2.44	3.29 ± 2.35	.093 *a*
Leg recovery	Tibialis anterior	5.12 ± 3.86	5.39 ± 2.51	6.84 ± 3.48	.040 *c*
Leg recovery	Biceps femoris	2.25 ± 1.28	2.65 ± 1.46	2.86 ± 1.14	.049 *a*
Leg recovery	Rectus femoris	0.77 ± 0.75	0.83 ± 0.79	1.15 ±.1.08	.017
Stroke cycle	Triceps brachii	13.12 ± 7.74	15.70 ± 9.02	18.63 ±.9.24	.000 *abc*
Stroke cycle	Biceps brachii	15.83 ± 6.03	18.78 ± 6.46	23.63 ± 8.93	.000 *abc*
Stroke cycle	Trapezius	16.55 ± 6.76	18.42 ± 8.41	18.55 ± 6.46	.622
Stroke cycle	Pectoralis	19.48 ± 10.68	25.56 ± 11.87	27.38 ± 13.95	.002 *b*
Stroke cycle	Gastrocnemius	10.95 ± 6.52	15.15 ± 8.92	19.77 ± 9.36	.000 *abc*
Stroke cycle	Tibialis anterior	17.24 ± 8.78	20.09 ± 7.60	24.99 ± 10.82	.012 *bc*
Stroke cycle	Biceps femoris	8.84 ± 3.17	11.51 ± 4.47	14.04 ±.4.54	.000 *abc*
Stroke cycle	Rectus femoris	9.26 ± 5.59	10.95 ± 5.64	14.26 ± 7.95	.000 *abc*

Note: Integrated electromyography (iEMG) is amplitude normalised to the relative maximal voluntary contraction (MVC) and phases are time normalised to % of the stroke cycle. *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%.

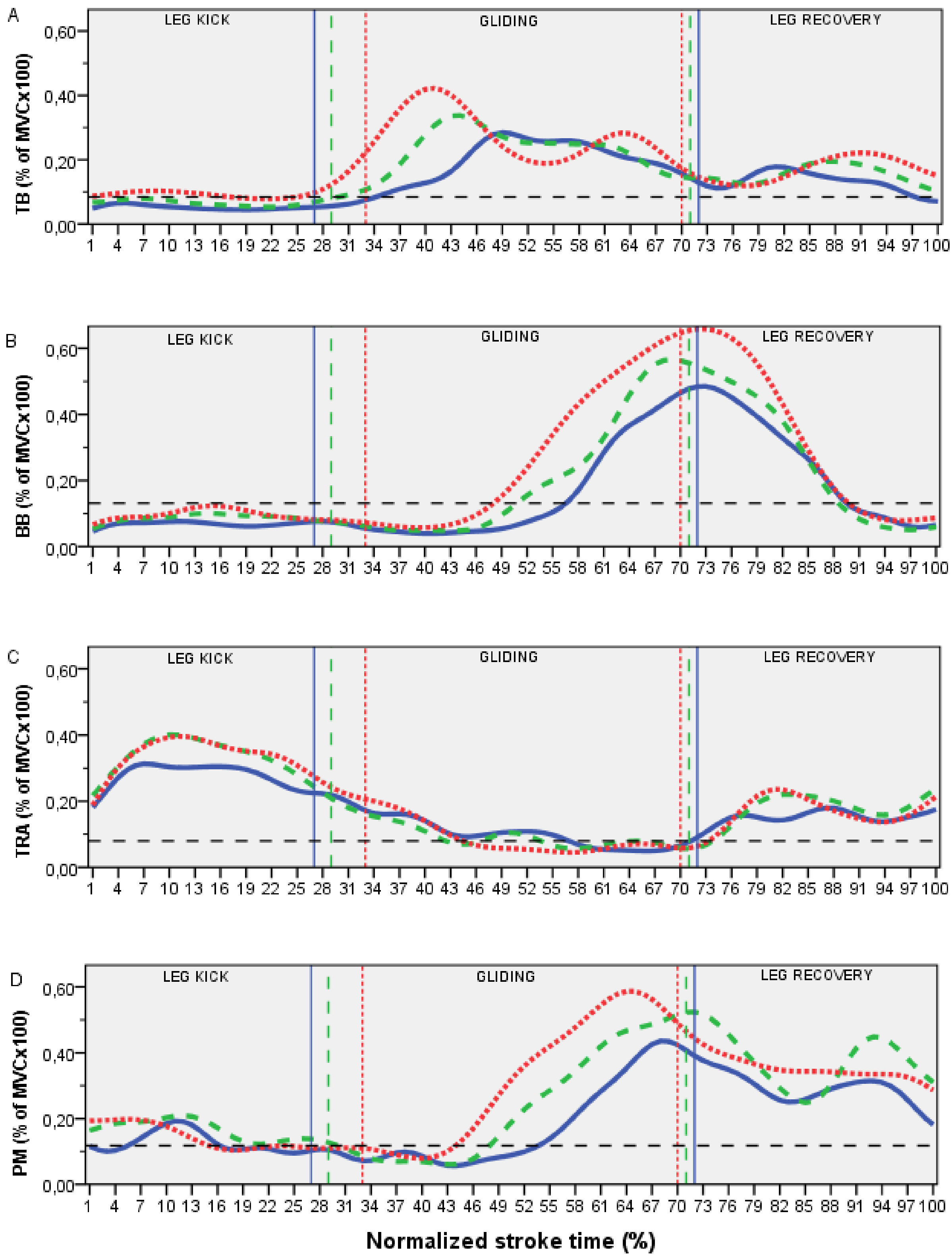

Figure 4. Average muscle activation (avgC) pattern during breaststroke swimming at 60-80-100% of maximal effort for the four muscles of the upper limb during the three phases of the complete stroke cycle. Amplitude is normalised to the relative maximal voluntary contraction (MVC) and time is normalised 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 time 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).

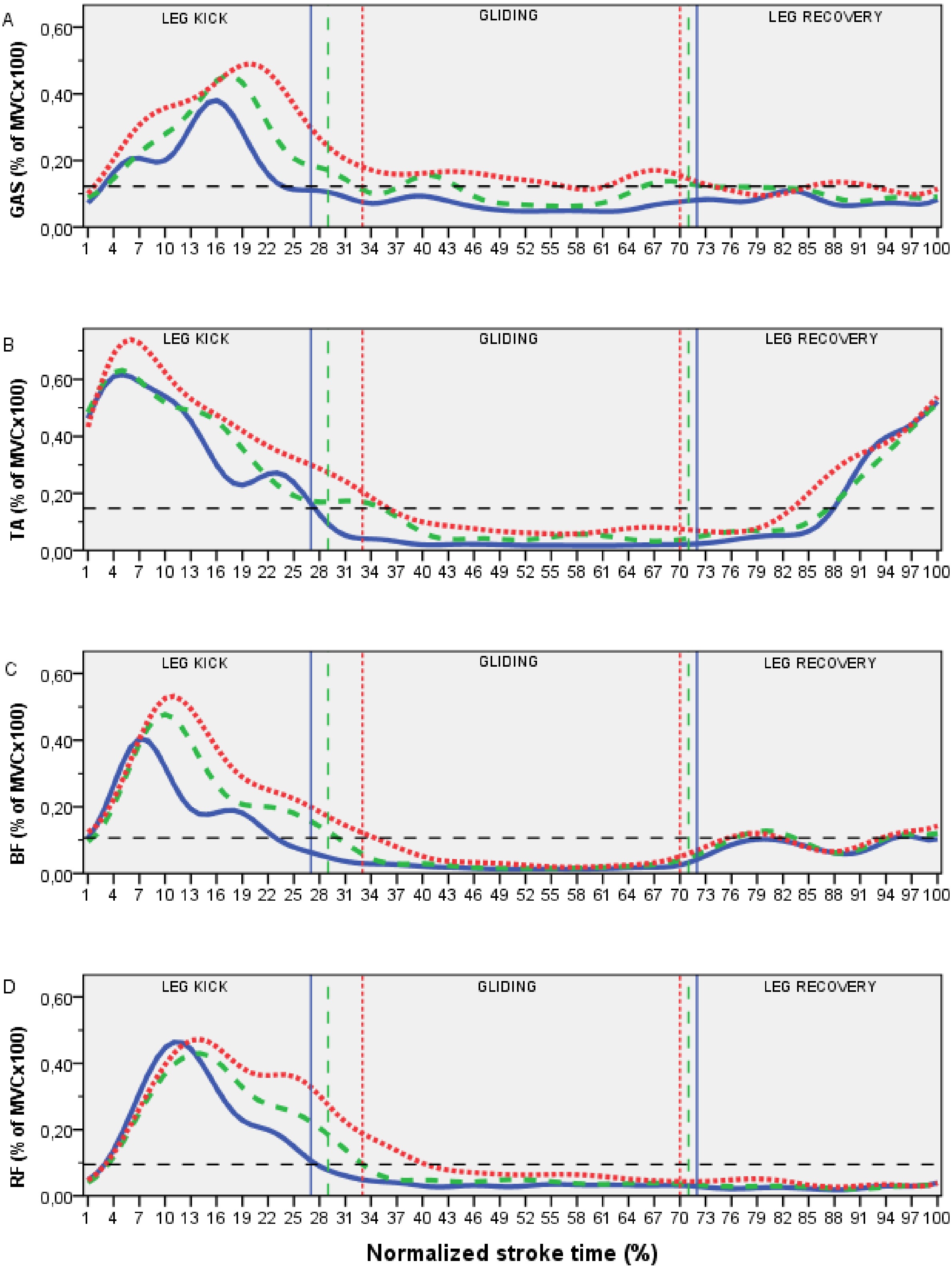

Figure 5. Average muscle activation (avgC) pattern during breaststroke swimming at 60-80-100% of maximal effort for the four muscles of the lower limb during the three phases of the complete stroke cycle. Amplitude is normalised to the relative maximal voluntary contraction (MVC) and time is normalised 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 time 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.

During gliding, TRA decreased its activation compared to the previous 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 leg recovery 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 leg recovery (Figure 5). The upper limb muscles showed high activation at the beginning and finished their contribution to generate propulsion with the in-sweep. 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 “lifted” out of the water before the arms shooting forward and contributing to the upper body streamline position together with PM.

Discussion

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

Kinematics

The significant decrease for cycle length, 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 length 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/SL that will determine the velocity (Maglischo, 2003).

Since absolute time and length remained similar during the leg kick 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 I, as well as a better upper body streamline at the beginning of this phase.

The longer gliding during BR 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 time spent and length during this phase in order to increase velocity with increasing effort.

There was a significant decrease in absolute time and increase in velocity with increasing effort while length remained constant during leg recovery. 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) propulsion in BR 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 leg 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 this phase for all effort levels indicating a strong contribution in maintaining the upper body in a streamlined position. The PM activated earlier at 80% and 100% when compared to 60%. This indicates a stronger contribution for improving the streamline of the upper body with increased effort as well as a more continuous coordination mode between the arms and legs (Maglischo, 2003) and further studied by (Leblanc, Seifert & Chollet, 2009; Seifert et al., 2011). 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 glide indicating that full knee extension occurred after the completion of the in-sweep, see Table Ia, where the largest knee angle occurred during the gliding 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 gliding at around 65% into the SC. The activation observed in GAS at 100% also indicates a more active role in streamlining the feet during gliding in order to actively decrease the drag. The longer gliding is unique to BR 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 velocity was found during this phase (Table Ia) when the legs are in a streamlined position for reducing the active drag, while the upper limb is moving for generating forward propulsion. The TB, BB and PM showed its peak amplitude and iEMG as they act as the prime movers for generating propulsion and increasing velocity through this phase. The TB is 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 out-sweep. At 100% TB started activating during the leg kick phase while at 60% and 80% during the gliding phase. This might indicate an earlier and more active role in decreasing the time gap between continuous overlap in propulsion from the lower and upper limbs. The co-activation of TB and BB towards the end of this phase was also found by Yoshizawa et al. (1976) showing an active flexion of the forearm. 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 leg recovery important muscular activities were found in order to bring the legs quickly back to the beginning for the next leg kick. 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 leg recovery indicated that other muscles also contribute in this phase, for example the gluteal muscles 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

A limitation of this study is that we only had cameras underwater. This meant that markers on the upper body and arms went out of the water during certain parts of the stroke cycle, e.g. arm recovery and breathing. 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 & 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

Measuring muscle coordination and kinematics is important to evaluate swimming technique. While kinematics can roughly be observed by coaches, the use of 3D with AT makes the evaluation of kinematic variables more accurate. In order to have efficient propulsion and good working economy the right muscle coordination is highly important. Contrary to kinematics, it is not possible to observe the muscle coordination. Watching the final of the Olympic Games or the World Championship, there is a noticeable difference in swimming technique between athletes. This was also indicated among the swimmers participating in this study during the kinematic and EMG parameters and can be seen in the results with a larger standard deviation. Therefore, individual differences in swimming technique due to different e.g. anthropometrical, strength, flexibility, endurance, work economical constitutions should be considered when using EMG and kinematics for evaluating BR swimming technique.

Conclusion

Increased velocity with increasing effort came from a significant decrease in length during the gliding phase combined with a decrease in the time spent for the gliding and leg recovery phases. In addition the knee angle at the beginning of the leg kick 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 gliding 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 gliding. 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, muscular participation, and kinematics assessed in this study with elite BR swimmers contribute to a better understanding of the stroke, and could be used as a reference for teaching BR technique.

Acknowledgments

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.

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Study 4 in full text

Guignard, B., Olstad, B.H., Escobar, D.S., Lauer, J., Kjendlie, P.L., & Rouard, A.H. (2015).

Different muscular recruitment strategies among elite breaststrokers.

International Journal of Sports Physiology and Performance. Advance online publication. doi:10.1123/ijspp.2014-0498

Note. This article will be published in a forthcoming issue of the *International Journal of Sports Physiology and Performance*. The article appears here in its accepted, peer-reviewed form, as it was provided by the submitting author. It has not been copyedited, proofread, or formatted by the publisher.

Section: Brief Report

Article Title: Different Muscular Recruitment Strategies Among Elite Breaststrokers

Authors: Brice Guignard[a], Bjørn Harald Olstad[b], David Simbaña Escobar[a], Jessy Lauer[a,b], Per-Ludvik Kjendlie[b], and Annie Hélène Rouard[a]

Affiliations: [a]Laboratory of Exercise Physiology, EA4338, University of Savoy, Le Bourget du Lac cedex, France. [b]Norges Idrettshøgskole, Norwegian School of Sport Sciences (NIH), Department of Physical Performance, Oslo, Norway.

Journal: *International Journal of Sports Physiology and Performance*

Acceptance Date: March 13, 2015

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DOI: http://dx.doi.org/10.1123/ijspp.2014-0498

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—SUBMISSION TYPE: BRIEF REPORT—

Different muscular recruitment strategies among elite breaststrokers.

AUTHORS: Brice Guignard[a], Bjørn Harald Olstad[b], David Simbaña Escobar[a], Jessy Lauer[a,b], Per-Ludvik Kjendlie[b], Annie Héléne Rouard[a].

[a]Laboratory of Exercise Physiology, EA4338, University of Savoy, 73376 Le Bourget du Lac cedex, France.

[b]Norges Idrettshøgskole, Norwegian School of Sport Sciences (NIH), Department of Physical Performance, Oslo, Norway.

CORRESPONDING AUTHOR: B. Guignard, Laboratory of Exercise Physiology, EA4338, University of Savoy, 73376 Le Bourget du Lac Cedex, France.

Tel: +33 6 37 03 89 01, E-mail: brice.guignard@etu.univ-savoie.fr

PREFERRED RUNNING HEAD: Breatstrokers' muscular strategies.

ABSTRACT WORD COUNT: 248

TEXT-ONLY WORD COUNT: 1499

NUMBER OF FIGURES: 3

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ABSTRACT

Purpose: The purpose of this study was to investigate electromyographical (EMG) profiles characterising the lower limb flexion-extension in an aquatic environment, for high-level breaststrokers. **Methods:** The 2D breaststroke kick of one international- and two national-level female swimmers was analysed during two maximal 25-m swims. The activities of M. biceps femoris, rectus femoris, gastrocnemius and tibialis anterior were recorded. *Results:* The breaststroke kick was divided in three phases, according to the movements performed in the sagittal plane: push phase (PP) covering 27% of the total kick duration; glide phase (GP) 41%, and recovery phase (RP) 32%. Intra-subject reproducibility of the EMG and kinematics was observed from one stroke cycle to another. Additionally, important inter-subject kinematic reproducibility was noted whereas muscular activities discriminated the subjects: the explosive PP was characterised by important muscular activation peaks. During the recovery, muscles were likewise solicited for S1 and S2 while the lowest activities were observed during GP for S2 and S3, excepted for S1, who maintained major muscular solicitations. **Conclusions:** The main muscular activities were observed during PP, to perform a powerful lower limb extension. The most skilled swimmer (S1) was the only one to solicit his muscles during GP to reach actively a better streamlining. Important activation peaks during RP correspond to the limbs acting against water drag. Such differences in EMG strategies among an elite group highlighted the importance of considering the muscular parameters used to control effectively the intensity of activation among the phases for a more efficient breaststroke kick.

KEYWORDS: Biomechanics, Swimming, EMG, Lower limb, Flexion-extension.

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INTRODUCTION

Breaststroke is characterised by intra-stroke velocity fluctuations, caused by discontinuity in propulsive actions.[1] The major source of propulsion stems from the cyclic and symmetrical movements of the lower limbs.[1] A recent study underlined that the flexion-extension in the sagittal plane is the main component of the 3D breaststroke kick,[2] without forgetting this movement cannot be separated from others planes of motions.

Few former studies focused on kick EMG evaluation despite its major implication in the breaststroke propulsion. These works mainly described the flat breaststroke style using a small number of subjects[3]. This kind of flexion-extension movement has been extensively investigated in terrestrial sports (squat[4] and ventral flexion-extension[5]), underlining the main contribution of lower limbs in the sagittal plane. The purpose of the present work was to characterise from muscular and kinematical point of views the lower limbs flexion-extension movements during the breaststroke kick performed by high-level swimmers.

METHODS

Participants and testing procedures:

To consider the possible effect of expertise level on EMG results, one international (S1) and two national-level (S2 and S3) female swimmers volunteered for this study (19.7 ± 7.4 years; 1.68 ± 0.04 m; 67 ± 5.5 kg). They were informed about the procedure and signed a consent approved by the local ethics committee. After a standard warm-up consisting of low- to moderate-intensity swimming, the swimmers performed two 25-m maximal effort breaststroke bouts at the velocity corresponding to their best time on 100-m race with 30 s rest between the two tests.

Data collection:

The activities of four muscles chosen for their main contribution in the breaststroke flexion-extension[3] (medial head of M. gastrocnemius (GAS), tibialis anterior (TA), rectus

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femoris (RF) and biceps femoris (BF)) were recorded at 1000Hz, according to ISEK placement recommendations.[6]

The electrodes (20 mm inter-electrodes distance) were waterproofed and connected to a pre-amplifier (band-pass filter of 8–500 Hz, input impedance>100 MΩ, common mode rejection ratio was 110 dB and gain of 1000). The signals were telemetrically transmitted in real time.[7]

The flexion-extension was measured using the motion capture technique at a frequency of 100Hz (Qualisys Track Manager 2.6, Qualisys, Gothenburg, Sweden). Six reflective markers (diameter of 19 mm) were fixed on the right side of the body (trochanter major, lateral femoral condyle, medial and lateral malleolus, first and fifth metatarsals). As the main component of the movement is in the sagittal plane, three angles were selected: the ankle (A), from fifth metatarsal, lateral malleolus and lateral femoral condyle markers; knee (K) from lateral malleolus, lateral femoral condyle and trochanter major markers; and thigh (T) from lateral femoral condyle, trochanter major markers and antero-posterior axis.

Data treatment:

From markers coordinates, the knee angle in the sagittal plane was calculated as follows (A: marker positioned on the lateral malleolus, K: on the lateral femoral condyle, T: on the trochanter major):

$$\widehat{AKT} = \arccos\left(\frac{\overrightarrow{KA} \cdot \overrightarrow{KT}}{\left\|KA \cdot KT\right\|}\right)$$

Similar computation was done for articular ankle and segmental thigh angles.

The lower limbs stroke was divided in three phases: the push phase (PP), starting with maximal sagittal knee flexion to full ankle extension attained at the beginning of the glide (GP), and followed by the recovery phase (RP), from the beginning of knee flexion to the maximal knee flexion value (adapted from Maglischo).[8]

Raw sEMG signals were full-wave rectified and smoothed using a low- and high-pass filter of 500Hz and 20Hz, respectively (MATLAB 2008a software, MathWorks Inc., Natick, MA, USA). The signal was normalised regarding a dynamical value corresponding to the movement.[9] For each participant and muscle, the rectified EMG was calculated for the full stroke and partitioned in 50 ms windows to find the $iEMG_{max}$. The rectified EMG was expressed in percentage of $iEMG_{max}$ among the phases.[9]

The reproducibility of the strokes was evaluated for the three lower limbs angles (Figure 1(a)) and from two parameters for each muscle: (i) the EMG peak value (PV) and (ii) the time between two consecutive EMG peaks (TP) over 5 cycles of the stable portion of the test (Figure 1(b)). The Intra Stroke (IS) variability for each participant and muscle was determined thanks to coefficients of variation: $PV_{IS}(\%)=PV_{SD}/PV_{mean}\times100$ for EMG and $TP_{IS}(\%)=TP_{SD}/TP_{mean}\times100$ for time duration, according to Taylor and Bronks.[10]

RESULTS

The inter-cyclic time variability was lower than 7% for TP_{IS} and slightly higher for the EMG peak (from 10% for BF to 23% for RF with the highest SD close to 18% for RF). Such results were considered as an acceptable variability.[10] Due to the good inter-cyclic movement reproducibility, the relationships between angles and EMG parameters will focus on one stroke only.

The total stroke duration ranged from 1.31 s for S2 to 1.58 s for S1 with a strong homogeneity among the subjects for relative phase durations. The glide phase, recovery phase and push phase represented respectively 41.0 ± 1.0%, 32.7 ± 4.9% and 26.3 ± 4.2% of the total stroke cycle. Similar angular patterns were observed for the three subjects and the three phases (Figure 2(a)).

PP was characterised by a concomitant extension of the thigh and knee followed by the ankle. Angle vs. time curve presented steep slopes, indicating high angular velocities

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especially for the knee (548 ± 46 deg/s). These kinematics were supported by important muscular solicitations for the three high-level subjects (Figure 2(b)). GP was considered as a passive phase since few angular modifications were observed for the three swimmers. It was characterised by low activations for S2 and S3, contrary to S1. RP displayed a simultaneous thigh-knee flexion, followed by the ankle, with important muscular activities for S1 and S2, contrary to S3. Mean and SD muscular activities for each phase are presented on Figure 3.

DISCUSSION

EMG and kinematics recordings were stable from one cycle to another for each participant, reflecting the task automation related to the high expertise level. Homogeneous inter-subject kinematics confirmed previous findings about explosive extensions.[4] The locomotion adopted to perform the breaststroke kick conditioned the muscular activities and common tendencies emerged from the results. The highest muscular activities were observed during PP, the feet taking support on inert masses of fluid, hence loading the muscles. During the extension, kinetic energy is transferred to these masses of water. Consequently, high feet velocities were reached at this moment of the stroke. The flexion (RP) is performed by the lower limbs against water resistance, as previously noted in flat breaststroke.[3] Consequently, despite the non-propulsive leg actions in RP, important muscular activities were found for S1 and S2. Similar results were observed in water walking with continuous activations both in propulsive (stance) and recovery (swing) phases due to the resistive aquatic environment.[11]

However, among this group of high-level swimmers, different muscular solicitations emerged to produce similar movements. The international-level swimmer was the only one to maintain recruitment during GP, to control actively her streamlined position to limit the drag increase. Such basic level of activity during the glide could relate to a dynamic preparation for legs recovery during RP. For their part, national-level subjects considered GP as a rest phase, with low muscular solicitations.

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Similarly, S3 presented low muscle activities for the four studied muscles during RP, supposing the contribution of others muscles (semimembranosus and semitendinosus). This is consistent with results found during a terrestrial lower limb flexion performed in ventral position.[5]

Finally, S2 presented an eccentric activation of RF, with a peak at the end of RP immediately followed by a concentric action during PP. This combination resembled a stretch-shortening cycle,[12] which has never been observed in swimming. This deserves further investigation.

The aquatic environment and load fluctuations might be responsible for these individualistic EMG activation patterns among high-level swimmers. Despite similar swimming velocities, the subjects interact differently with the fluid when they performed the breaststroke kick (i.e. use of different swimming techniques), thereby impacting the EMG profiles.

PRACTICAL APPLICATIONS:

This study presented relevant muscular parameters discriminating efficient breaststroke kick among a group of elite swimmers. Since measurements of such muscular behaviours are not systematic in swimming evaluation because of their costs, our findings are of value to target the evaluation more strictly. Despite the inter-subject variability (likely related to the small sample size), those EMG parameters were pertinent enough to unveil distinct, yet yielding quite similar outputs, motor control strategies. We therefore encourage the use of EMG as a powerful diagnosis tool.

CONCLUSIONS:

Kinematic and EMG inter-cycle reproducibility reflected the task automation characterising expertise. Yet, strong between-subject variability in muscular activities was observed, possibly due to (i) the differences of level expertise in our swimmers' sample, (ii)

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the important and inconstant resistances encountered in an aquatic environment, and (iii) the specificity of the breaststroke locomotion, characterised by two phases performed against major resistances. This study revealed that muscular activity variations might be described for a similar movement performed by elite swimmers in a constraining environment. Future analyses must consider a larger number of swimmers to reinforce present findings. Moreover, the three-dimensional nature of the movement and the implication of the trunk in the propulsion must be included in further investigations since propulsive areas (i.e. mainly the feet) are not reduced to a simple backward push.

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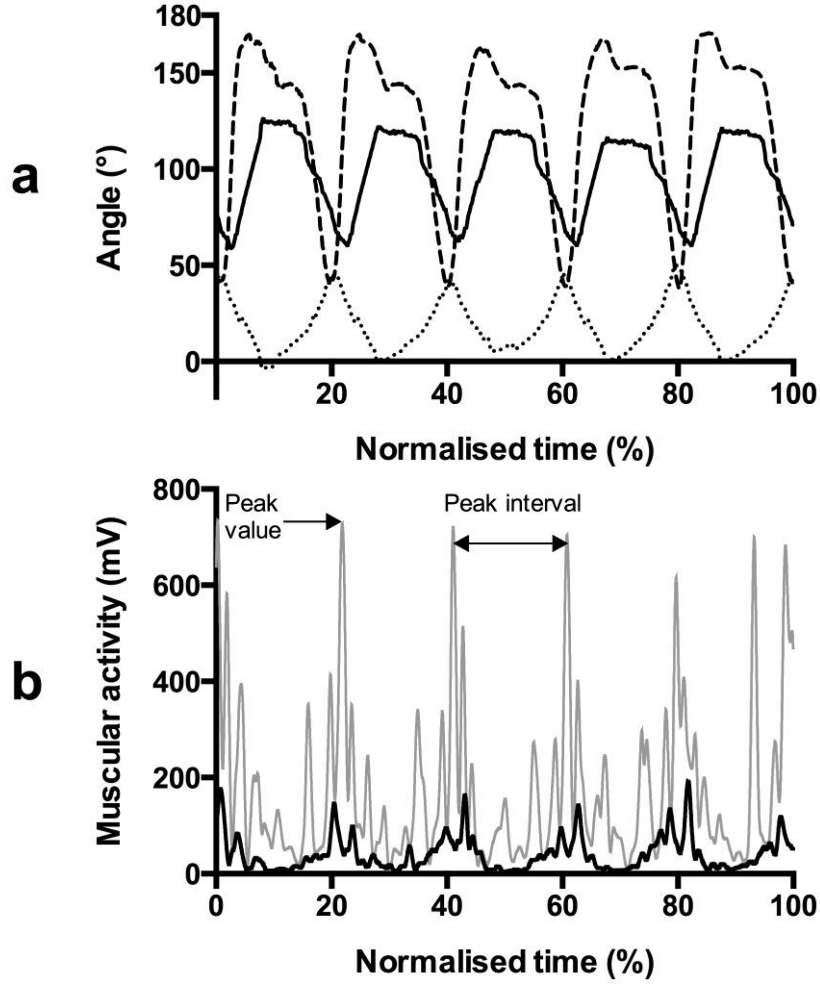

Figure 1: Reproducibility of kinematical (a) and muscular parameters (b) for one participant over five stroke cycles. Reproducibility was computed for thigh (dot lines), knee (dash lines) and ankle (solid lines) angles and from peak value and peak interval parameters on TA (black curve) and GAS (grey curve) muscles.

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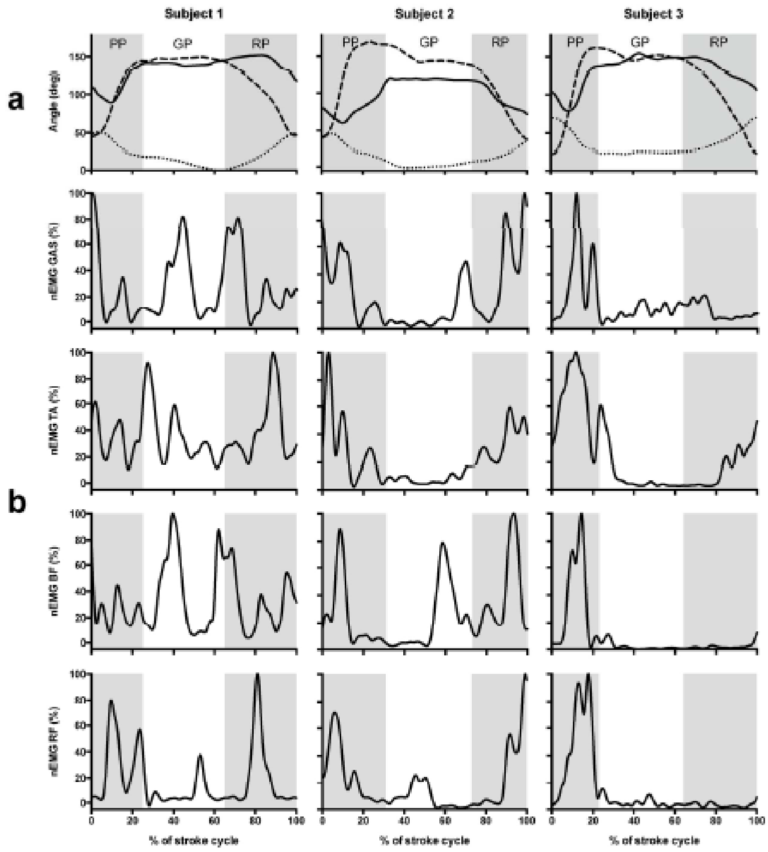

Figure 2: Three main joints kinematics of the thigh (dot lines), the knee (dash lines) and the ankle (solid lines) (a) and normalised EMG of the four muscles (b) during the three phases of one stroke cycle for the three participants (PP: push phase, GP: glide phase and RP: recovery phase).

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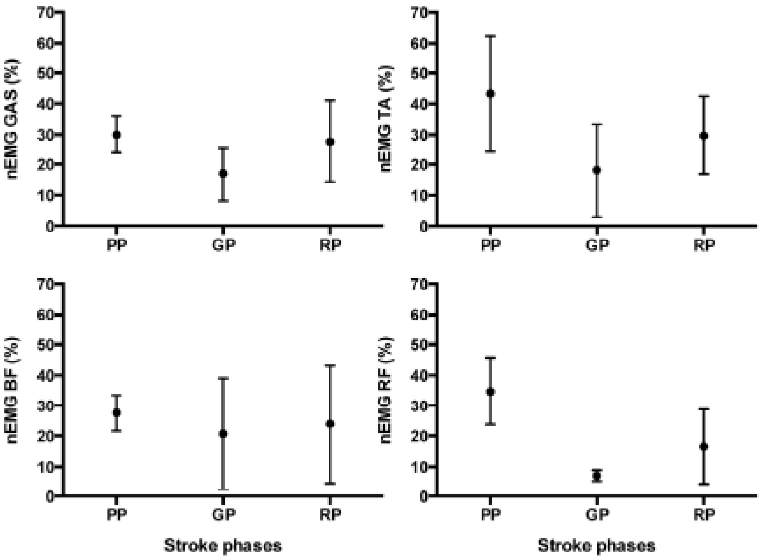

Figure 3: Effect of the stroke phase on the muscular activity for the four studied muscles and the three subjects (mean ± SD).

Study 5 in full text

Olstad, B.H., Zinner, C., Vaz, J.R., Cabri, J., & Kjendlie, P.L.

Muscle coordination differences in world champions, world-class and national elite breaststroke swimmers.

Submitted to *Scandinavian Journal of Medicine and Science in Sports*.

Muscle coordination differences in world champions, world-class and national elite breaststroke swimmers

BJØRN HARALD OLSTAD[1], CHRISTOPH ZINNER[2], JOÃO ROCHA VAZ[3], JAN M. H. CABRI[1] & PER-LUDVIK KJENDLIE[1]

[1]*Department of Physical Performance, Norwegian School of Sport Sciences, Sognsveien 220, 0806 Oslo, Norway,*

[2] *Department of Sport Science, Julius-Maximilians-University Würzburg, Judenbühlweg 11, 97082 Würzburg, Germany and*

[3] *Faculty of Human Kinetics, University of Lisbon, Estrada da Costa, 1499-002 Cruz Quebrada - Dafundo, Lisbon, Portugal*

Corresponding author:

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

Running head: Breaststroke EMG coordination world champions

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 aim of this study was to describe the differences in world champions, world-class (WC) and national elite (NE) breaststroke swimmers in terms of muscular coordination with support of kinematical variables. Surface electromyography of the triceps brachii, biceps brachii, trapezius, pectoralis major, gastrocnemius, tibialis anterior, biceps femoris and rectus femoris was collected in four WC and four NE. Underwater cameras were used for automatic 3D kinematic analysis. The participants swam 25 m of breaststroke at 60%-80%-100% effort. Each stroke cycle was divided into three phases: leg kick, gliding and leg recovery. The results indicated that a distinct difference in muscle coordination pattern exists for the triceps brachii and biceps brachii between swimmers. Furthermore, a more economical use of the muscles in WC was found in comparison to NE. In WC swimmers, muscle activation was characterized as: Gastrocnemius towards the end of the leg kick, rectus femoris at the beginning of gliding and earlier activation in pectoralis major and earlier activation in biceps femoris during leg recovery. Since muscle coordination differs between WC and NE, these components may be important determinants of swimming performance and could be used for developing an optimal muscular coordination for swimming breaststroke at the highest level.

Keywords: *swimming, EMG, motion analysis, biomechanics*

Introduction

In swimming, only a few athletes become world champions while others remain at the national elite level. In order to reach the highest mean velocity throughout a competition several factors play an important role e.g. anthropometrics, strength, flexibility, working economy and psychology. Additionally, race tactics and swimming technique play an important role for the performance outcome. Many of the physiological factors that are required for performing at the world class (WC) level are well documented (Davison et al., 2009; Savage & Pyne, 2011; Smith et al., 2002), as well as kinematic data of the swimming movements captured in 2D and more recently in 3D (Barbosa et al., 2011; Seifert, L. et al., 2011b). Therefore, an important focus would be to look at the skeletal muscle itself, developed to create mechanical force and produce movement (Medved & Cifrek, 2011).

Kinesiological EMG can be used to identify coordination, synchronization and intensity of muscle activity. It is an established subfield of modern locomotion biomechanics and contributes to the understanding of human movement and performance. Muscular activation must be optimal during the different stroke phases and plays an important role for applying force against the aquatic resistance and for effectively positioning the propulsive areas (i.e. hands and feet). Coactivation between muscles is generally involved in these processes to determine movement efficiency, safety, controlling the precision and velocity of the movement, and for stabilizing a single joint (Basmajian & De Luca et al., 1985; Frost et al., 1997; Neumann, 2010). While coactivation is necessary during certain movements (Draganich et al., 1989) excessive activation of antagonist muscle is associated with increased metabolic cost and a “waste” of energy (Frost et al., 2002; Hortobagyi et al., 2011; Huang et al., 2012).

The first published recordings of underwater EMG signals in breaststroke swimming to compare two groups of swimmers with different performance levels were conducted by Ikai et al. (1964). They described activation patterns of 15 muscles for Olympic swimmers and members of the University swimming club and found a common basic pattern of muscular activities. They concluded that the muscle activation patterns from Olympic swimmers were more effective. Furthermore, they found that the triceps brachii (TB) worked mainly in the early part of the arm stroke while the biceps brachii (BB) and pectoralis major (PM) contributed in the latter part of the movement. In addition tibialis anterior (TA), biceps femoris (BF) and rectus femoris (RF) worked during the leg kick simultaneously with the trapezius (TRA) during the gliding of the arms. Due to some methodological challenges, the absence of normalization and identification of stroke phases made it hard to compare groups. Later, Yoshizawa et al. (1976) compared Olympic swimmers (65-68 s for 100 m BR) to members of a University swimming club and average adults using EMG measurements of 14 muscles. Distinct differences in activation patterns between groups were found: Olympic swimmers had longer activation of the TA and better timing with the use of gastrocnemius (GAS) allowing a longer dorsiflexion of the foot resulting in a more effective kick. In the best swimmer, activity of the RF was observed during the first part of gliding, showing that full extension of the knee joint occurred after the feet were almost together. The Olympic swimmer also showed higher and earlier activity in the BB during the pull-phase in order to perform the elbow-up pull with earlier elbow flexion in order to achieve large propulsion.

Since these early studies the breaststroke technique has changed significantly through implementations of rule changes from the Fédération Internationale de Natation (FINA) (Persyn et al., 1992). Nowadays the swimmers use a breaststroke style with body undulation where the hands can break the water surface and the head can go under water on each stroke cycle (SC). These changes in breaststroke technique must likely induce some changes in the activation of the muscles, hence to the EMG activity. One study on the new breaststroke style with one international and two national level swimmers was conducted by Guignard et al. (2015a) in four leg muscles. They found that the international level swimmer was the only one to maintain muscle activity during the gliding phase in order to actively reach a better streamlining position.

Today there are only a few studies on muscle activation in water due to the methodological challenges of conducting EMG in water and many research questions are still unanswered, e.g. muscle activation patterns of modern day high level swimmers (Martens et al., 2015). It is important to understand whether muscle activation in modern style breaststroke technique can contribute to different performance levels in swimming. The purpose of this study was therefore to investigate the potential differences in world champions, WC and National Elite (NE) breaststroke swimmers related to the muscle coordination patterns for the complete SC and the three different phases of the breaststroke leg kick with support of kinematical variables during competition speed (100% of maximal effort). We hypothesized that WC swimmers would show a different and more economical muscle activation pattern than NE swimmers.

Materials and methods

Participants

Four WC breaststroke swimmers (medallists at international championships) including two females and two males (world champions) and four NE breaststroke swimmers (medallists at national championships) including two females and two males participated in this matched controlled group study (Table 1). 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.

Table 1. *Participant characteristics (means ± SD)*

n	Sex	Age (yrs.)	Body weight (kg)	Height (cm)	Streamline height (cm)	FINA-points (breaststroke)
2 World-class	Females	25.5 ± 4.0	66.2 ± 10.1	167.0 ± 1.4	213.0 ± 1.4	986.5 ± 10.6
2 World-class	Males	27.3 ± 1.7	86.6 ± 0.8	188.0 ± 2.8	243.3 ± 1.1	1009.0 ± 22.6
(world champions)						
2 National elite	Females	16.0 ± 1.9	63.9 ± 0.2	168.3 ± 6.0	210.5 ± 3.5	674.5 ± 29.0
2 National elite	Males	28.0 ± 12.1	83.1 ± 1.3	185.0 ± 2.8	235.8 ± 4.6	749.0 ± 4.2

FINA-points=the highest number of points for each swimmer regardless of distance or course.

Experimental protocol

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 the equipment including 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 verify the effort level (Borg, 1998), where 11, 15 and 19 score corresponded to 60%, 80% and 100% effort, respectively (Hill, 2010).

Surface electromyographic data collection

Muscle activation was recorded with surface EMG from eight muscles on the right side of the body: 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). 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 Ltda, Lisbon, Portugal) were positioned at the midpoint of the contracted muscle belly (Clarys & Cabri, 1993) in line with the direction of the muscle fibers. Anatomical references for the electrode placement were carried out according to the SENIAM recommendations (Hermens et al., 1999; Hermens et al., 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 and resistance during swimming.

Insulating tape was also used for fixing the cables to the body to avoid movement artefacts (Rainoldi et al., 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. The active sensors were connected to the bioPlux Research Input Box from Plux Ltda, Lisbon, Portugal using wires running inside a waterproof pouch with 8 analogue channels (12 bit). Before the main experiment, the quality of EMG was visually assessed in real time, both on land and under the water.

Kinematic data collection

A 3D underwater motion-capture system with automatic motion tracking (Qualisys, Gothenburg, Sweden), consisting of 10 Oqus 3 and 4 cameras (sampling frequency 100 Hz), were installed in the pool to record underwater movements. Due to malfunction, six cameras were used for recording some of the swimmers, but our tests of measuring accuracy were not affected. All cameras were equipped with 12 high power LED's and an active filtering hardware operation which reduced unwanted reflections from sunlight, bubbles and other particles and were placed inside a waterproof case. The cameras covered a volume of approximately 37.5 m^3, 10 m (*X*; horizontally) x 2.5 m (*Y*; width) x 1.5 m (*Z*; vertically). 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.

Passive, spherical markers with retro-reflective tape (Qualisys, Gothenburg, Sweden) developed to suit underwater usage (diameter 19 mm) with neutral buoyancy 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 metatarsal. Furthermore, four marker clusters were fixed on the thigh and shank according to (Cappozzo et al., 1997; de Leva, 1996).

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. Qualisys Track Manager 2.6 and 2.8 were used to track and process the anatomical markers on the swimmers' body. Swim velocity, stroke length (SL), phase time, stroke rate (SR) and knee angle for the complete SC and for each of the phases were measured. Based on the leg kick, each SC was divided in three phases: (1) leg kick: from the smallest knee angle during recovery until the first peak in knee angle (extension) during the leg kick, (2) gliding: from end of the leg kick to the beginning of active knee flexion for leg recovery, and (3) leg recovery: from end of gliding until the smallest knee angle. The leg kick was chosen for phase division due to its central role in generating propulsion and setting the rhythm of the stroke. In addition it provided reliable picture treatment since cameras where only placed underwater and markers on the upper body went out of the water during certain parts of the SC, e.g. arm recovery and breathing.

The raw EMG signals were visually inspected to assure its quality 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, 4th order Butterworth). Averaged EMG (EMG_{avg}) was calculated for each muscle during the SC. The EMG signals were amplitude normalised to the individual Maximal Voluntary Contraction (MVC). Because different phase durations were observed among the swimmers, each stroke phase was interpolated to 50 time points using Matlab. This allowed comparison between the swimmers with respect to muscle coordination within each phase.

For identifying muscular on- and offset, a threshold level of 20% of the peak EMG activation during the SC was selected for all muscles except for GAS, which showed a higher baseline activity and therefore the threshold level was set to 25% (Hug, 2011). Coactivation was expressed as the duration of agonist–antagonist activity above the threshold level divided by the duration of the SC or phase according to (Frost et al., 1997; Lamontagne et al., 2000). Electromyographic reproducibility was calculated using up to 10 SC at the different effort levels. Three to five SC at the stabilised swimming velocity of the last part of each swim at 60, 80 and 100% effort, were selected for further EMG and kinematic 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 one-way ANOVA were performed to test overall differences of the kinematic variables between the SCs and the different stroke phases at 60, 80 and 100% of maximal effort and level of confidence was set to 95% for statistical differences and to 90% for statistical tendencies.

Results

Kinematics

WC spent significantly less time during the leg kick and leg recovery phase, but spent more time during gliding. The largest difference in mean swimming velocity was found during the gliding phase with WC being 0.20 m/s faster at 60% of maximal effort and 0.13 m/s faster at 80% and 100% compared to NE.

WC had longer cycle length and travelled the furthest during the leg kick and gliding phase. Different values in the knee angle were found between the two groups with WC beginning the leg kick phase with a smaller knee angle while NE started the gliding and leg recovery phase with the largest knee angle. An overview of the kinematic results can be found in Table 2.

Table 2. *Time, length 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 gliding phase*

Kinematic variable	60% effort	*p*-value	80% effort	*p*-value	100% effort	*p*-value
Time for leg kick phase (s)						
World-class	0.40 ± 0.03	.041**	0.38 ± 0.04	.019**	0.38 ± 0.05	.448
National elite	0.50 ± 0.06		0.48 ± 0.05		0.43 ± 0.08	
Time for gliding phase (s)						
World-class	0.96 ± 0.08	.902	0.83 ± 0.09	.021**	0.62 ± 0.16	.722
National elite	0.98 ± 0.26		0.61 ± 0.11		0.59 ± 0.07	
Time for leg recovery phase (s)						
World-class	0.42 ± 0.04	.016**	0.39 ± 0.03	.042**	0.38 ± 0.05	.038**
National elite	0.55 ± 0.07		0.48 ± 0.05		0.46 ± 0.03	
Length of leg kick phase (m)						
World-class	0.44 ± 0.04	.226	0.47 ± 0.06	.402	0.50 ± 0.14	.638
National elite	0.51 ± 0.09		0.51 ± 0.06		0.46 ± 0.03	
Length of gliding phase (m)						
World-class	1.23 ± 0.18	.050*	1.12 ± 0.10	.007**	0.87 ± 0.19	.431
National elite	0.93 ± 0.09		0.76 ± 0.14		0.77 ± 0.11	
Length of leg recovery phase (m)						
World-class	0.32 ± 0.04	.368	0.31 ± 0.04	.069*	0.39 ± 0.07	.649
National elite	0.37 ± 0.10		0.41 ± 0.08		0.42 ± 0.11	
Total cycle length (m)						
World-class	1.99 ± 0.22	.342	1.89 ± 0.15	.207	1.75 ± 0.17	.483
National elite	1.81 ± 0.24		1.67 ± 0.27		1.66 ± 0.19	
Velocity in leg kick phase (m/s)						
World-class	1.10 ± 0.09	.111	1.23 ± 0.22	.263	1.27 ± 0.19	.443
National elite	0.98 ± 0.05		1.06 ± 0.17		1.15 ± 0.22	
Velocity in gliding phase (m/s)						
World-class	1.29 ± 0.18	.146	1.36 ± 0.21	.318	1.40 ± 0.19	.285
National elite	1.09 ± 0.08		1.23 ± 0.10		1.27 ± 0.11	
Velocity in leg recovery phase (m/s)						
World-class	0.75 ± 0.07	.293	0.77 ± 0.08	.360	1.02 ± 0.19	.552
National elite	0.66 ± 0.13		0.88 ± 0.20		0.92 ± 0.28	

Table 2. *Continued*

Kinematic variable	60% effort	*p*-value	80% effort	*p*-value	100% effort	*p*-value
Total cycle velocity (m/s)						
World-class	1.11 ± 0.13	.098*	1.18 ± 0.16	.338	1.27 ± 0.17	.293
National elite	0.94 ± 0.07		1.07 ± 0.15		1.13 ± 0.17	
Stroke rate (strokes/min)						
World-class	33.7 ± 1.5	.179	37.5 ± 2.9	.701	43.7 ± 5.1	.436
National elite	30.2 ± 4.4		38.6 ± 4.3		41.0 ± 4.2	
Knee angle, beginning of leg kick phase (°)						
World-class	44.0 ± 2.4	.476	43.0 ± 1.2	.636	42.5 ± 3.1	.893
National elite	45.6 ± 3.3		44.0 ± 3.6		42.9 ± 3.1	
Knee angle, beginning of gliding phase (°)						
World-class	165.4 ± 8.7	.300	164.8 ± 9.2	.224	165.6 ± 10.0	.447
National elite	171.5 ± 6.2		171.8 ± 4.8		171.1 ± 9.1	
Knee angle, beginning of leg recovery phase (°)						
World-class	155.2 ± 3.6	.331	158.4 ± 7.7	.587	154.6 ± 9.4	.236
National elite	159.2 ± 6.7		161.5 ± 7.5		161.8 ± 5.6	
Largest knee angle during gliding phase (°)						
World-class	175.0 ± 3.2	.880	175.7 ± 3.2	.700	174.8 ± 5.5	.542
National elite	175.4 ± 3.3		174.9 ± 2.4		176.7 ± 2.5	

Significant difference between groups ** $p < 0.05$ and tendency between groups * $p < 0.1$.

Electromyography

The individual muscle activation patterns remained constant throughout the different SC at all effort levels (an example for one swimmer in TB at 100% is presented in Figure 1), but individual differences were present. The results for the eight muscles are presented for 100% of maximal effort (competition speed).

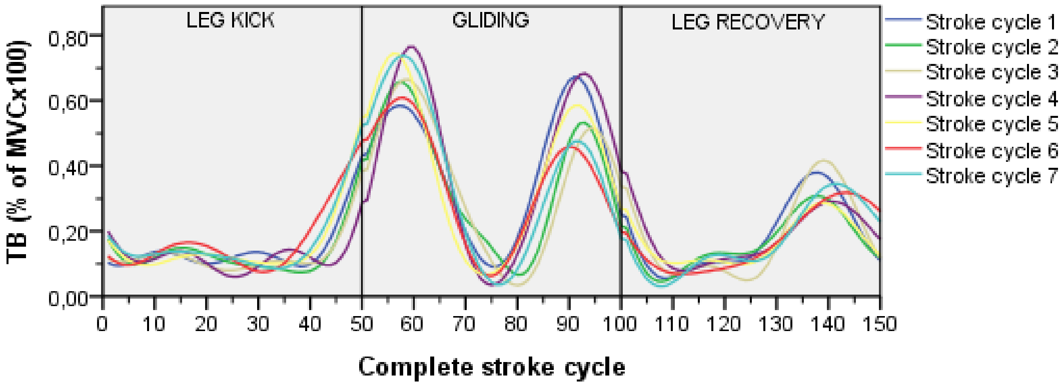

Figure 1. Average muscle activation pattern during seven complete stroke cycles for triceps brachii (TB) during 100% effort for a national elite swimmer. Amplitude is normalized to the relative maximal voluntary contraction (MVC) and time is normalized to the three stroke phases (50 points each).

Triceps and biceps brachii

The total average activation for NE in TB during the leg kick phase was 27.5%, while none of the WC showed activation beyond the threshold level (except for one swimmer during the last 6%). Three of the NE also showed activation beyond the threshold level in TB at the beginning of this phase. WC activated BB earlier into the gliding phase of the legs than NE, with 52% and 57% respectively. In addition, one world champion activated the BB 30% into this phase.

The TB showed most individual patterns with two and three peaks during the SC for NE while WC only showed one (one world champion had two peaks). One world champion had very high activation amplitude (around 80% of MVC) in the TB while very little activation was found for the BB (around 30% of MVC) while the other world champion showed the opposite amplitude pattern (Figure 2). For the other swimmers an even activation amplitude was found between these two muscles. An example of the muscle coordination through the SC from one world champion and one NE is presented in Figure 3A.

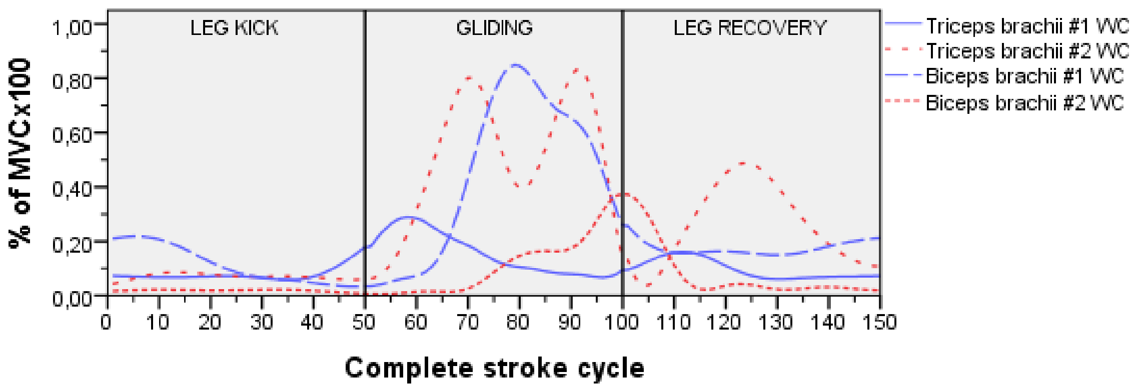

Figure 2. Average muscle activation pattern for two world-class (WC) swimmers during 100% effort. Amplitude is normalized to the relative maximal voluntary contraction (MVC) and time is normalized to the three stroke phases (50 points each).

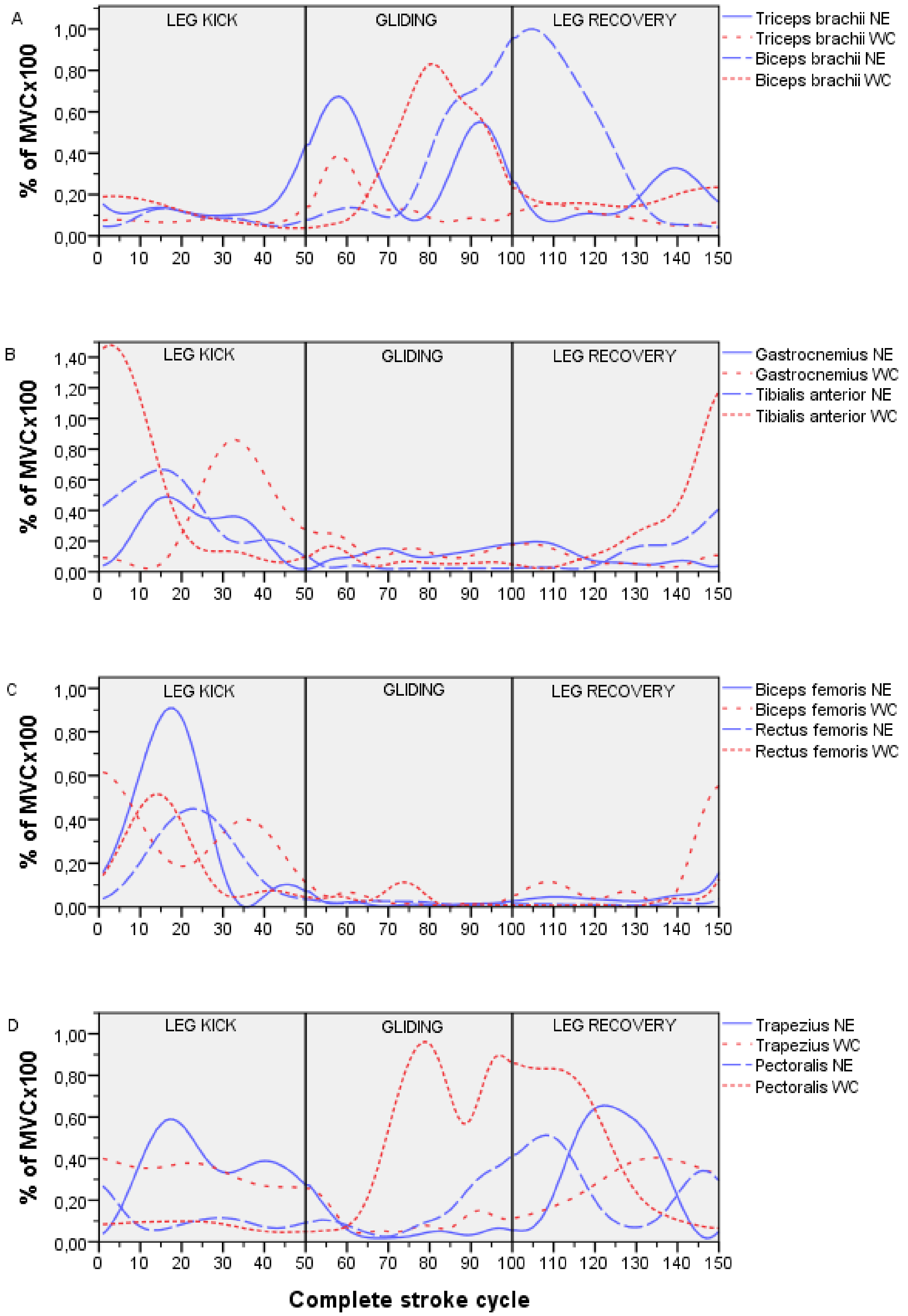

Figure 3. Average muscle activation pattern for one national elite (NE) and one world-class (WC) swimmer during 100% effort. Amplitude is normalized to the relative maximal voluntary contraction (MVC) and time is normalized to the three stroke phases (50 points each).

Gastrocnemius and tibialis anterior

All of the swimmers started the leg kick phase with activation in TA. National Elite activated TA for 81.5% while WC showed activation for 68% of this phase. Only the two world champions and one NE showed activation in GAS at the end of the leg kick. The WC showed activation in GAS at the beginning of the gliding phase while only one NE had GAS activated. The National Elite swimmers started activating TA at 50% into the leg recovery phase while WC activated TA for the last 45%. In addition two NE showed coactivation between GAS and TA towards the end of this phase. On the contrary to all the other participants, the two world champions showed no coactivation between GAS and TA during the whole SC. An example of the muscle coordination through the SC from one world champion and one NE is presented in Figure 3B.

Biceps and rectus femoris

Only one world champion started the leg kick phase with coactivation, but all of the swimmers showed coactivation between BF and RF during the leg kick phase. While all of the WC showed activation of RF during the beginning of the gliding phase, only one of the NE showed this activation pattern. WC started the leg recovery phase with a smaller knee angle than NE (154.6° vs 161.8°) and had on average BF activated for 40.5% of the leg recovery phase while NE only showed 29.5%. An example of the muscle coordination through the SC from one world champion and one NE is presented in Figure 3C.

Trapezius (pars descendens) and pectoralis major (pars clavicularis)

Out of the eight muscles tested, all swimmers showed the longest periods of activation for TRA and PM relative to the SC. Six of the swimmers including both the world champions had TRA activated throughout the leg kick phase. WC had joint activation for 37% of this phase, NE for 17%, while one of the world champions showed joint activation for 80%. A large difference between the two world champions and the other swimmers was seen in the gliding phase of the legs for PM. The two world champions activated PM for 71% of this phase while the other swimmers activated PM for 54.7%. In addition two NE only activated PM for the last 25% of this phase. An example of the muscle coordination through the SC from one world champion and one NE is presented in Figure 3D.

Discussion

Distinct differences were found for the muscle activation pattern and coactivation between the two world champions, WC and NE for the eight muscles tested in this study.

Triceps and biceps brachii

The most distinct difference in muscle coordination patterns between the swimmers were found for TB and BB.

The fact that no WC showed activation of the TB until the last 6% of the leg kick phase, while three of the NE showed activation at the beginning of this phase indicates that NE starts their leg kick before the upper body has reached full streamline position as we observed in the motion capture. In addition the activation in TB from NE during this phase indicates that they are using TB during their streamline position of the upper body on the contrary to WC who is able to rest this muscle and save energy during the non-propulsive phase of the arms.

According to Maglischo (2003) the outsweep of the arms during breaststroke is a non-propulsive phase and the forward velocity of the body will decelerate through this phase. Therefore, the main purpose of the outsweep is to align the hands in a backward-facing position as soon as possible through a flexion of the arms at the elbow initiating BB activity and placing them in a position allowing acceleration through the insweep. Therefore, similar to Yoshizawa et al. (1976) WC showed an earlier activation in BB at 52% into the gliding phase of the legs while NE started activating later at 57%. In addition one of the world champions activated at 30% into this phase indicating an even earlier elbow flexion and orientation of the propulsive surface earlier in the stroke.

While the other swimmers maintained high activation amplitude in both muscles, one world champion had very high activation in TB and very little activation for BB (middle distance swimmer - 100m (W1)). The other world champion had very high activation in BB while very little activation was observed for TB (sprinter - 50m (W2)). Both swimmers started the arm pull with activating TB as they reached their arms forward to extend their SL and pre-activate the muscle. W2 activated TB 6% before the end of the leg kick phase while W1 activated 5% into the gliding phase. Both of these technical aspects have been identified through the timing of the arms and legs by Maglischo (2003) as overlap and continuous timing and further studied by (Leblanc et al., 2009; Seifert, L. et al., 2011a). The overlap timing used by W2 is characterized with the beginning of the outsweep occurring before the legs come together while the continuous timing of W1 begin the outsweep immediately after the legs come together. These two timing techniques also correspond to the swimmers primary competition distances where W2 is a 50 m breaststroker while W1 is a 100 m breaststroker (Chollet & Seifert, 2010).

In addition, W2 had high activation in BB early during the gliding phase indicating an earlier change of hand direction to generate forward propulsion and lift (Yoshizawa et al., 1976). This could also be a strategy for W2 to generate a more explosive stroke with a higher lift of the upper body out of the water in order to bring the hands forward over the water surface explosively. In addition, W2 is a more upper body swimmer who generates less velocity during the leg kick phase than W1. W2 then compensates with a higher SR, shorter SL and more explosive arm movements during the gliding phase of the legs. W1 used a flatter stroke with a more shallow kick (ankle depth) and less vertical hip movement as identified in the motion capture and therefore is not required to put the same amount of activation on BB. This could also be an advantage for W1 that generates high velocity during the leg kick and can therefore maintain streamline for a longer period of time with longer SL and lower SR in order to swim more economically and maintain the stroke for longer distances.

Gastrocnemius and tibialis anterior

All swimmers started the leg kick phase with activation in TA indicating that they had a good dorsiflexion of the ankle at the beginning of this phase. On the contrary to Yoshizawa et al. (1976) which found longer activation for TA in the Olympic swimmers allowing a longer dorsiflexion of the foot, the NE in this study showed a longer TA activation than WC. The better timing of the use of GAS found by Yoshizawa et al. (1976) for the best swimmer which prevented early plantar flexion of the foot seen in poor swimmers, resulting in a less effective kick, was still present in both groups. Nevertheless, NE held their TA activation too long hindering the active squeeze and lift of the feet towards the end of the leg kick phase as seen in the two world champions. This could be explained by the technical evolution in breaststroke where today's technique have a deeper leg extension followed by a rising undulation of the feet during the insweep (Seifert, L. et al., 2011b). Towards the end of this phase only the two world champions and one NE had only activation of the GAS similar to the finding of Yoshizawa et al. (1978) indicating that these swimmers were able to forcefully squeeze the legs together with good plantar flexion of the ankle in order to generate higher feet velocity and forward propulsion. The WC, but only one NE showed activation in GAS at the beginning of the gliding phase suggesting that the WC may be better in streamlining their ankle to reduce resistance during the gliding phase.

Yoshizawa et al. (1978) investigated Olympic swimmers and found strongly activated TA at the beginning and during the leg recovery phase. On the contrary, no swimmers in our study showed activation in TA during the beginning of this phase indicating that the technique has changed and that today's technique takes further advantage of the up kick motion with plantar flexion of the ankle. This is also in accordance with the technique description from Maglischo (2003) where the lower legs and feet are recovered forward and just before the feet reach the buttocks they are swept outwards and forward indicating a contribution from TA. NE showed activation for TA during the last 50% of this phase while WC for the last 45% indicating an earlier transition from plantar flexion to dorsiflexion of the ankle in NE as seen in the motion capture. This indicates that the WC use their muscles in a better way for reducing drag during the leg recovery and have a quicker transition from plantar flexion to dorsiflexion and could therefore be one reason why they spent less time during this phase. On the contrary to the six other participants the two world champions showed no coactivation of GAS and TA during the whole SC indicating an optimal movement economy between dorsi- and plantar-flexion of the ankle in order to generate propulsion and to reduce drag while still maintaining ankle stability. This is in accordance with studies done with walking (Hortobagyi et al., 2011) and running (Frost et al., 1997; Frost et al., 2002; Moore et al., 2014), where it was found that excess coactivation was an inefficient process that increased the metabolic cost. In cycling, excess coactivation was observed in less skilled cyclists, but not in elite cyclist, too (Chapman et al., 2008).

Biceps and rectus femoris

All of the swimmers showed coactivation between BF and RF during the leg kick phase indicating that knee extension was generated with high power. Only one world champion started this phase with coactivation. Muscle coactivation between quadriceps and hamstrings is considered very important for knee joint stabilization during many athletic activities (Kellis, 1998). Guignard et al. (2015a) found high angular velocities for the knee during the leg kick in breaststroke corresponding to a powerful extension and can be considered a strategy for better controlling the precision and safety of the movement (Guignard, B. et al., 2015b).

All of the WC, but only one NE showed activation in RF during the beginning of the gliding phase, which may indicate as shown in Yoshizawa et al. (1976) that full knee extension occurs after the completion of the in-sweep in the legs. For the WC this might indicate an active strategy in performing a body undulation with the hip slightly flexed and with the buttocks lifted up towards the water surface as seen in the motion capture.

Cappaert et al. (1996) and Leblanc et al. (2005) found that the best swimmers spent a shorter time in the leg recovery phase. This is in agreement with our data that showed a significant shorter time spent during leg recovery phase for WC compared to NE. WC spent a significantly shorter time during the leg recovery phase compared to NE. This may be due to a smaller knee angle in WC at the beginning of this phase taking advantage of the body undulation to generate forward velocity of the body. In addition WC showed activation in BF for 40.5% of the leg recovery phase while NE only showed 29.5%. This indicates that WC use BF more actively to bring the heels up to the buttocks for a quicker leg recovery as seen in Table 2 as well as indicated in (Yoshizawa et al., 1976) to ensure minimum forward flexion of the thigh to keep water resistance at a minimum.

Trapezius (pars descendens) and pectoralis major (pars clavicularis)

While TRA is not a direct antagonistic muscle to PM they are both important muscles for the performance in breaststroke swimming. Therefore, we chose to present them together.

Out of the eight muscles tested, all swimmers showed the longest periods of activation for TRA and PM relative to the SC. Six of the swimmers including both world champions had TRA activated throughout the leg kick phase suggesting that TRA is activated to maintain upper body streamline position during the leg kick. In addition WC had activation in both PM and TRA for 37% of this phase, NE for 17%, while one of the world champions showed activation in both muscles for 80% revealing that WC may further optimizes and lengthen upper body streamline position.

Colman et al. (1998) and Van Tilborgh et al. (1988) found that the hand in-sweep is often the most propulsive phase of the arm stroke. This can be linked to the activation in PM, which is a powerful muscle to generate forward propulsion from the upper limb. A large difference between the two world champions and the others swimmers was seen during the propulsive arm pull (gliding phase of the legs) for the PM. The two world champions activated their PM for the last 71% of this phase while the other swimmers activated PM for only 54.7% on average. In addition three of the NE did not start activating PM until the last 25% of this phase. This implies that the world champions are able to generate earlier and higher forward propulsion from the arm pull while the legs are gliding.

In summary, our results have proved textbook descriptions of breaststroke technique from a muscular activation perspective and showed that a distinct difference in muscle coordination pattern exists between swimmers of different performance levels. The best swimmers began their arm pull at the end of the leg kick phase with activation in TB for extending their reach during the outsweep followed by an early catch with activation in BB while thereafter initiating an early activation of PM for a powerful insweep. In WC swimmers, muscle activation for the legs was characterized as follows: GAS towards the end of the leg kick, RF at the beginning of gliding and an earlier activation in BF during leg recovery. WC swimmers also spent significantly shorter time for the leg kick and leg recovery than NE. In conclusion, the longer coactivation and less economical use of the muscles found in NE can relate to a greater metabolic cost while swimming, which could be detrimental to performance (Moore et al., 2014).

Perspectives

While many of the physiological demands and biomechanical factors required for reaching an international performance level are well documented and implemented among coaches and swimmers little is known about possible differences at the muscular level. The findings of this study shed light on a new area which coaches and swimmers could utilize and implement in their daily training regime in order to reduce the metabolic cost and learn how to develop an optimal muscular recruitment pattern for swimming breaststroke at the highest level. A key factor to an economical and thus successful performance is to limit excessive activation and coactivation at the muscular level in order to decrease the metabolic cost. Furthermore, to emphasize the movement pattern and muscular recruitment strategy in order to perform the leg kick and leg recovery with a more explosive movement pattern to limit the time spent during these phases. These findings should therefore be taken into account when developing teaching and training methods as well as exercises for swimmers and movement analysis for researchers within breaststroke swimming.

Acknowledgments

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.

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Appendix A

Approval from Regional Committees for Medical and Health Research Ethics of Southern Norway (REK)

Universitetslektor Bjørn Harald Olstad
Norges idrettshøgskole
pb. 4014 Ullevål stadion

Regional komité for medisinsk og helsefaglig forskningsetikk Sør-Øst A (REK Sør-Øst A)
Postboks 1130 Blindern
NO-0318 Oslo

Telefon: 22 84 46 66

E-post: post@helseforskning.etikkom.no
Nettadresse: http://helseforskning.etikkom.no

Dato: 21.12.2010
Deres ref.:
Vår ref.: 2010/2893a

2010/2893a Muskelbruk og kinematikk i moderne brystsvømming

Vi viser til søknad om forhåndsgodkjenning av ovennevnte forskningsprosjekt. Søknaden ble behandlet av Regional forskningsetisk komité for medisinsk og helsefaglig forskningsetikk i møtet 2. desember 2010. Søknaden er vurdert i henhold til lov av 20. juni 2008 nr. 44, om medisinsk og helsefaglig forskning (helseforskningsloven) kapittel 3, med tilhørende forskrift om organisering av medisinsk og helsefaglig forskning av 1. juli 2009 nr 0955.

Prosjektleder: universitetslektor Bjørn Harald Olstad

Forskningsansvarlig: Norges idrettshøgskole

I dette prosjektet vil man studere aktiviteten i muskulatur ved elektromyografi under forskjellige forhold hos svømmere på ulike nivå. Målet med studien er å kartlegge muskelaktiveringsprofilen i kinematikk hos av svømmere på ulik nivå. Denne kunnskapen skal bidra til økt forståelse for den moderne brystvømmingsteknikken og kartlegge hvor spesifikke vanlig drill- og styrkeøvelser er.

Det skal rekrutteres 15-30 svømmer til forsøkene. Det er utarbeidet et informasjonsskriv med samtykkeerklæring for deltakerne etter gjeldende standard.

Elektromyografien gjennomføres med overflateelektroder og skal gjøres under den vanlige treningen. Testen vil gjennomføres over 2 til 3 dager. Forsøkspersonene vil ikke "bli utsatt for noe mer enn det du gjøre i din daglige trening". For deltakerne kan testen bidra til å utvikle teknikk og muskelbruk "som kan brukes i videre trening for å øke prestasjonen". Forsøket kan også gi verdifull kunnskap om bruk av EMG i vann. Trenere vil få mer spesifikk kunnskap om hva som kreves for å bli en topp internasjonal brystsvønner og om hensiktsmessig trening.

Personidentifiserbare data skal slettes ved prosjektslutt 31.12.2012.

Slik prosjektet er framstilt i søknaden vurderer komiteen ikke formålet som å "skaffe til veie ny kunnskap om helse og sykdom" men om å komme fram til bedre treningsmetoder. Det benyttes etablerte metoder og kjent medisinsk kunnskap. Prosjektet vurderes derfor til å ligge utenfor helseforskningslovens virkeområde.

<u>Vedtak:</u>

Etter søknaden fremstår forskningsprosjektet som et systematisk opplegg for å utvikle bedre treningsmetoder. Undersøkelsen faller derfor utenfor helseforskningslovens virkeområde, jf. § 2, og kan gjennomføres uten godkjenning av REK.

Vi gjør oppmerksom på at det for behandling av personopplysninger i prosjektet er nødvendig med tillatelse fra personvernombudet.

Komiteens vedtak kan påklages til Den nasjonale forskningsetiske komité for medisin og helsefag, jfr. helseforskningsloven § 10, 3 ledd og forvaltningsloven § 28. En eventuell klage sendes til REK sør-øst A. Klagefristen er tre uker fra mottak av dette brevet, jfr. forvaltningsloven § 29.

Vennligst oppgi vårt saksnummer/referansenummer i korrespondansen.

Med vennlig hilsen

Gunnar Nicolaysen (sign)
Professor
Leder

Jørgen Hardang
Jørgen Hardang
Komitésekretær

Kopi: Norges idrettshøgskole ved øverste administrative ledelse
jan.cabri@nih.no

Appendix B

Approval from Norwegian Social Science Data Services (NSD)

Norsk samfunnsvitenskapelig datatjeneste AS
NORWEGIAN SOCIAL SCIENCE DATA SERVICES

NSD

Harald Hårfagres gate 29
N-5007 Bergen
Norway
Tel: +47-55 58 21 17
Fax: +47-55 58 96 50
nsd@nsd.uib.no
www.nsd.uib.no
Org.nr. 985 321 884

Per-Ludvik Kjendlie
Seksjon for fysisk prestasjonsevne
Norges idrettshøgskole
Postboks 4014
0806 OSLO

Vår dato: 12.01.2011 Vår ref: 25476 / 3 / KS Deres dato: Deres ref:

KVITTERING PÅ MELDING OM BEHANDLING AV PERSONOPPLYSNINGER

Vi viser til melding om behandling av personopplysninger, mottatt 07.11.2010. All nødvendig informasjon om prosjektet forelå i sin helhet 07.01.2011. Meldingen gjelder prosjektet:

25476	*Muskelbruk og kinematikk i moderne brystsvømming*
Behandlingsansvarlig	*Norges idrettshøgskole, ved institusjonens øverste leder*
Daglig ansvarlig	*Per-Ludvik Kjendlie*
Student	*Bjørn Harald Olstad*

Personvernombudet har vurdert prosjektet og finner at behandlingen av personopplysninger er meldepliktig i henhold til personopplysningsloven § 31. Behandlingen tilfredsstiller kravene i personopplysningsloven.

Personvernombudets vurdering forutsetter at prosjektet gjennomføres i tråd med opplysningene gitt i meldeskjemaet, korrespondanse med ombudet, eventuelle kommentarer samt personopplysningsloven/-helseregisterloven med forskrifter. Behandlingen av personopplysninger kan settes i gang.

Det gjøres oppmerksom på at det skal gis ny melding dersom behandlingen endres i forhold til de opplysninger som ligger til grunn for personvernombudets vurdering. Endringsmeldinger gis via et eget skjema, http://www.nsd.uib.no/personvern/forsk_stud/skjema.html. Det skal også gis melding etter tre år dersom prosjektet fortsatt pågår. Meldinger skal skje skriftlig til ombudet.

Personvernombudet har lagt ut opplysninger om prosjektet i en offentlig database, http://www.nsd.uib.no/personvern/prosjektoversikt.jsp.

Personvernombudet vil ved prosjektets avslutning, 31.12.2015, rette en henvendelse angående status for behandlingen av personopplysninger.

Vennlig hilsen

Bjørn Henrichsen

for Katrine Utaaker Segadal

Kontaktperson: Katrine Utaaker Segadal tlf: 55 58 35 42
Vedlegg: Prosjektvurdering
Kopi: Bjørn Harald Olstad, Glimmerveien 28, 1155 OSLO

Personvernombudet for forskning

Prosjektvurdering - Kommentar

Prosjektnr: 25476

Prosjektet er lagt frem for Regional komité for medisinsk og helsefaglig forskningsetikk (REK). REK vurderer prosjektet til å ligge utenfor helseforskningslovens virkeområde.

Prosjektet er et samarbeid med University of Edinbourgh, University of Iceland og Deutsche Sporthochschule Köln, som vil være tilstede på deler av forsøkene og også få tilgang til dataene som blir samlet inn. Ombudet anbefaler at behandlingen av data og ansvarsfordeling formelt er avklart mellom institusjonene og anbefaler at det utarbeides en databehandleravtale jf. personopplysningsloven § 15.

Personvernombudet finner at behandlingen av personopplysninger i prosjektet kan hjemles i personopplysningsloven § 8 første alternativ (samtykke).

Det inngår personer under 18 år i utvalget. Deres foreldre/foresatte samtykker til at de kan delta i prosjektet.

Prosjektslutt er angitt til 01.01.2014. Datamaterialet vil oppbevares med personidentifikasjon til utgangen av 2015 i påvente av konkrete oppfølgingsstudier. Senest innen 01.01.2016 vil datamaterialet være anonymisert. Med anonyme opplysninger forstås opplysninger som ikke på noe vis kan identifisere enkeltpersoner i et datamateriale, verken direkte gjennom navn eller personnummer, indirekte gjennom bakgrunnsvariabler eller gjennom navneliste/koblingsnøkkel eller krypteringsformel.

Personvernombudet minner om at eventuelle oppfølgningsstudier må meldes i god tid før de skal igangsettes.

Appendix C

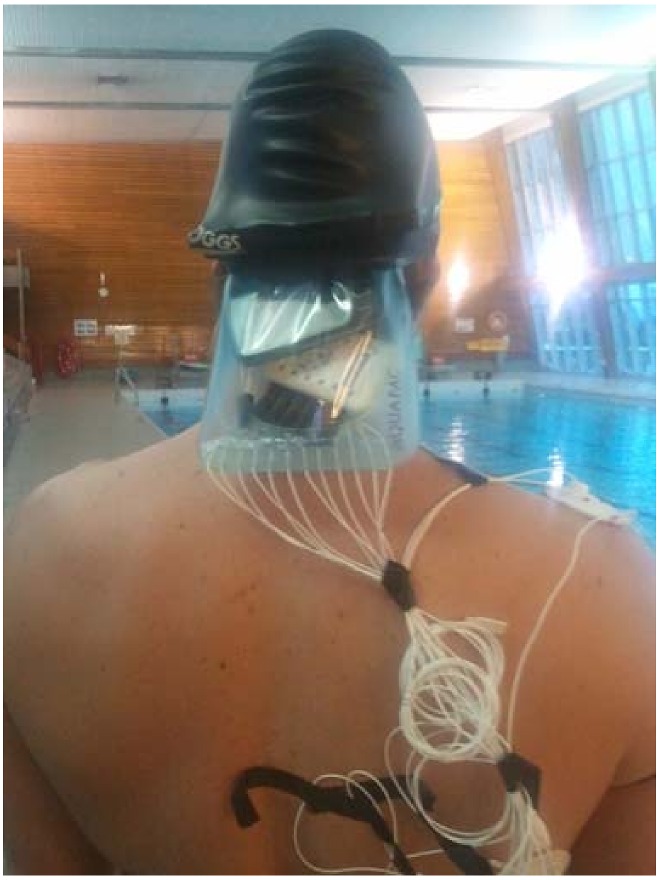
Study information and consent form

Informasjon for deltagelse i vitenskapelig forsøk

forsøksperson o 18 år

Du er ønsket til å delta i det første studiet i et større vitenskapelig forskingsprosjekt hvor målet er å bidra til økt forståelse for den moderne brystsvømmingsteknikken og kartlegge hvor spesifikke vanlige drill- og styrkeøvelser (land og vann) er. Muskelbruken i brystsvømming vil bli registrert ved hjelp av elektromyografi (EMG) og den kinematiske analysen vil foregå ved hjelp av 3D analyser fra videofilming over og under vann. EMG i vann er tidligere ikke blitt gjort i Norge og det første studiet vil undersøke reliabiliteten ved å måle muskelaktiviteten med EMG i vann på åtte muskler. I tillegg vil vi samle data mens dere svømmer de fire svømmeartene, undervannstak i bryst og glifasen under vann. Forskningen blir gjennomført av Bjørn Harald Olstad med veiledere Per-Ludvik Kjendlie og Jan Cabri og heter: ”Muskelbruk og kinematikk i moderne brystsvømming”. Vi har også et samarbeid med University of Edinbourgh, University of Iceland og Deutsche Sporthochschule Köln som vil være tilstede på deler av forsøkene og også få tilgang til dataene som blir samlet inn.

Forsøkene innebærer at du må komme på Norges Idrettshøgskole ved tre anledninger, og gjennomføre noen tester. Den første testdagen tar ca en time og gjennomføres bare på land. De to påfølgende testdagene tar ca. 2 timer og 15 minutter og her vil dere også bli testet i vannet. Dere vil få EMG elektroder festet til åtte muskler på kroppen og ledninger fra disse vil bli koblet til en forsterker som blir lagt i en vanntett pose sammen med en mottager. Posen plasseres innunder badehetten. Se bilde.



Testprotokoll:

Hudpreparering – huden blir vasket med alkohol der elektrodene skal festes 5*5cm. Hvis det er mye hår på disse stedene så vil vi måtte barbere bort dette. Elektrodeplasseringen vil bli merket med vannfast tusj slik at disse blir festet på nøyaktig samme sted under alle testdagene. Enkelte andre anatomiske landemerker vil også merkes med vannfast tusj.

Testdag 1:

3*MVC (maksimale kontraksjoner av musklene) på land for de åtte musklene

Måling av vekt, høyde og leddutslag i ankel-, hofte- og skulderledd.

Testdag 2 og 3:

3*MVC på de samme åtte musklene på land

3*MVC på de samme åtte musklene i vann

10 minutter med rolig svømming

Deretter vil dere også bli filmet under vann mens dere svømmer:

4*50m – en av hver svømmeart, start 2 minutter og 30 sekunder, i randomisert rekkefølge

3*fraspark fra veggen i strømlinje

3*undervannstak i bryst

3*10m butterfly kick under vann med fraspark fra veggen

3*MVC på de samme åtte musklene i vann

3*MVC på de samme åtte musklene på land

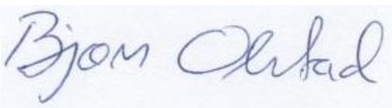
Det er ingen andre ubehag enn det som er vanlig under undervisningen dere har hatt i svømming. Fordelene med at du deltar er at du får se deg selv på video under vann, og at du kan lære om og forbedre svømmeteknikken din. Dessuten vil du lære om muskelbruk under aktivitet og EMG analyser. Dere vil også være de første i Norge til å gjennomføre svømming med EMG utstyr.

Alle opplysningene fra forskningen vil publiseres / skrives ut, men DET VIL IKKE STÅ DITT NAVN PÅ NOEN RAPPORTER. Det er bare forskerne som kan se på resultatene slik at ditt navn forekommer. Generelt vil vi følge alle rutiner for databehandling og anonymisering av forskningsmateriale, som pålagt av Norsk Sammfunnsvitenskapelige Datatjeneste.

Du deltar i forsøkene på frivillig grunnlag og kan når som helst avbryte eller trekke deg fra forsøkene uten at det vil få konsekvenser for deg.

Du er velkommen til å stille spørsmål dersom du lurer på noe.

Jeg kan treffes på telefon 930 61 946 eller e-mail bjorn.harald.olstad@nih.no



Vennlig Hilsen

Bjørn Harald Olstad

Forsøksleder / Doktorgradsstudent

Samtykke erklæring for deltagelse i vitenskapelig forsøk

myndige

1. Bjørn Harald Olstad er doktordradsstudent ved Norges Idrettshøgskole og ønsker deg til deltagelse i et forskningsprosjekt. Tittelen på prosjektet er "Muskelbruk og kinematikk i moderne brystsvømming".

2. Du er informert om at formålet med det første studiet er å undersøke reliabiliteten av å måle muskelaktivitet ved hjelp av elektromyografi (EMG) i vann på åtte muskler. I tillegg vil det bli samlet inn data mens dere svømmer testprotokollen beskrevet under.

Forsøkene er deler av et større prosjekt på Norges Idrettshøgskole.

3. Forsøkspersonene vil delta i forsøket på Norges Idrettshøgskole. Det innebærer informasjon, preparering av huden før utstyret settes på, oppvarming og tilvenning til testutstyret samt selve testingen, som består av

a) 3*MVC (maksimal muskelkontraqksjon) på åtte muskler på land, i vann, i vann og på land igjen ved hjelp av EMG,
b) svømme 4*50 meter, en av hver svømmeart, (med lang pause mellom hver, start 2,5 minutter) hvor man blir filmet under vann samtidig som man svømmer med EMG utstyret, 3*fraspark fra veggen i strømlinje, 3*undervannstak i bryst og 3*10m butterfly kick under vann.
c) måling av høyde, vekt, bevegelsesutslag i ankel-, hofte- og skulderledd,

All testig vil foregå med sikre og utprøvde metoder. Testfasilitetene og utstyret kan dere komme og se på i forkant om dette er ønskelig og det henvises til bildet i informasjonsskrivet.

4. Det er ingen annen risiko eller ubehag utover det som er normalt under en vanlig svømmeundervisningsøkt i bassenget. Sikkerheten blir ivaretatt av de tilstedeværende testledere.

5. Det finnes ingen andre måter å gjennomføre målingene på.

6. Fordelene med deltagelse i et slikt studie for deg er at du kan se deg selv på video under vann og gjennom dette forbedre din svømmeteknikk ved feedback fra forsøkslederen. Det er mulig å lære mye nyttig om svømming. Dessuten vil du lære om muskelbruk under aktivitet, EMG analyser og være de første i Norge til å gjennomføre svømming med EMG utstyr.

7. Jeg forstår at dataene fra studiet kan publiseres, men at din identitet eller navn IKKE vil offentliggjøres. Forsøksdataene vil kodes slik at det ikke er mulig å identifisere personer. Bare forsøkslederen og veiledere vil ha tilgang til datamateriale koblet til navn. Datamaterialet vil bli lagret til utgangen av 2015 for å evt. kunne brukes i oppfølgingsstudier og vil innen 1.1.2016 bli slettet.

8. Jeg har forstått at det ikke vil være noen form for økonomisk kompensasjon til forsøkspersonene.

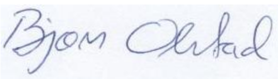
9. Jeg har forstått at alle spørsmål kan rettes til forsøkslederen, tlf 930 61 946, email bjorn.harald.olstad@nih.no

10. Jeg har lest ovenstående informasjon. Forsøksdeltagelsen er blitt meg forklart gjennom denne samtykke erklæringen. Jeg forstår at deltagelsen er frivillig, og at forsøkspersonene når som helst, og uten videre konsekvenser kan trekke seg fra deltagelsen i dette studiet. Ved underskrift på denne samtykke erklæringen frasier jeg meg ikke noen juridiske rettigheter. En kopi av dette skjemaet er blitt gitt til meg.

Jeg, ________________________________, har lest denne erklæringen, og samtykker min deltagelse i prosjektet.

Underskrift og dato: ____

11. Jeg bekrefter at jeg har informert om deltagelsen i dette studiet med formål, fremgangsmåter, fordeler og risiko, og har svart på spørsmål som blir stilt, samt gitt forsøkspersonene kopi av dette skjema.



Vennlig Hilsen

Bjørn Harald Olstad

Doktorgradsstudent, Norges idrettshøgskole

Informasjon for deltagelse i vitenskapelig forsøk

forsøksperson u 18 år

Du er ønsket til å delta i det første studiet i et større vitenskapelig forskingsprosjekt hvor målet er å bidra til økt forståelse for den moderne brystsvømmingsteknikken og kartlegge hvor spesifikke vanlige drill- og styrkeøvelser (land og vann) er. Muskelbruken i brystsvømming vil bli registrert ved hjelp av elektromyografi (EMG) og den kinematiske analysen vil foregå ved hjelp av 3D analyser fra videofilming over og under vann. EMG i vann er tidligere ikke blitt gjort i Norge og det første studiet vil undersøke reliabiliteten ved å måle muskelaktiviteten med EMG i vann på åtte muskler. I tillegg vil vi samle data mens dere svømmer de fire svømmeartene, undervannstak i bryst og glifasen under vann. Forskningen blir gjennomført av Bjørn Harald Olstad med veiledere Per-Ludvik Kjendlie og Jan Cabri og heter: "Muskelbruk og kinematikk i moderne brystsvømming". Vi har også et samarbeid med University of Edinbourgh, University of Iceland og Deutsche Sporthochschule Köln som vil være tilstede på deler av forsøkene og også få tilgang til dataene som blir samlet inn.

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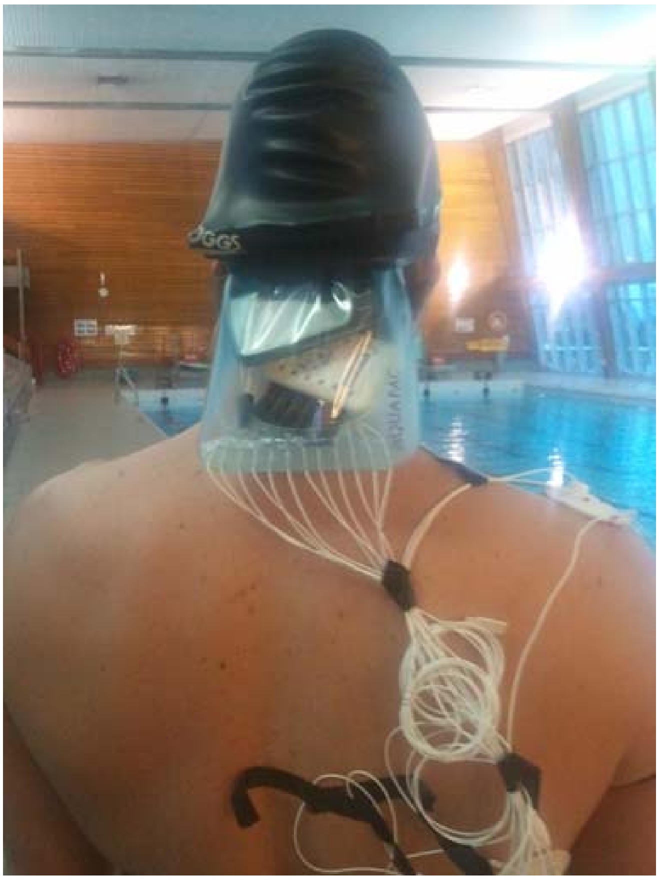

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3*10m butterfly kick under vann med fraspark fra veggen

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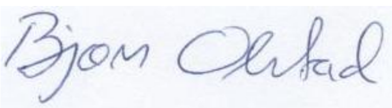

Vennlig Hilsen

Bjørn Harald Olstad

Forsøksleder / Doktorgradsstudent

Samtykke erklæring for deltagelse i vitenskapelig forsøk

forsøksperson u 18 år

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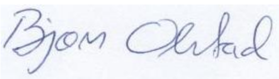
Jeg, __________________________, har lest samtykke erklæringen, og samtykker herved at jeg som foresatt for:

_________________________ tillater dennes deltagelse i forskningsprosjektet.

Underskrift og dato: __________

11. Jeg bekrefter at jeg har informert om deltagelsen i dette studiet med formål, fremgangsmåter, fordeler og risiko, og har svart på spørsmål som blir stilt, samt gitt forsøkspersonene kopi av dette skjema.



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