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Biomechanical analysis of backstroke to breaststroke turns in age-group swimmers: An intervention study

(The interplay between the kinematics, dynamometric, hydrodynamics and electromyography factors)

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DEDICATION

In memory of my father, Kamdee CHAINOK

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1. Chainok, P., de Jesus, K., Mourão, L., Fonseca, P., Zacca, R., Fernandes, R., Vilas-Boas, J.P. (2021). Biomechanical features of backstroke to breaststroke transition techniques in 11-13 years old age-group swimmers. Frontiers in Sports and Active Living, 54.

2. Chainok, P., Lauer, J., Gonçalves, P., Fernandes, R., Vilas-Boas, J.P. (2021). Backstroke to breaststroke turns muscular activity. A study conducted in age group swimmers. Manuscript submitted for publication.

3. Chainok, P., Borgonovo-Santos. M., Machado, L., de Jesus, K., Abraldes, A., Fernandes, R., Vilas-Boas, J.P. (2021). Backstroke to breaststroke turns performance in age - group swimmers: Hydrodynamic characteristics and pull-out strategy. International Journal of Environmental Research and Public Health, 18(4), 1858.

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LIST OF ABBREVIATIONS

a	Mean acceleration for each gliding
ABST	The AdaBoost
AI	Artificial Intelligence
ANOVA	Analysis of variance
ANN	Artificial neural network
C_D	Drag coefficient
C_{D1}	Drag coefficient of the first gliding position
C_{D2}	Drag coefficient of the second gliding position
C_p	Total square error
CFD	Computer fluid analysis
CG	Center of gravity
CI	Contextual interference
D	Drag force
D_1	Drag force of the first gliding position
D_2	Drag force of the second gliding position
DPO	Dominant push-off force
DPO_X	Dominant peak push-off force while feet pushing to the left or right
DPO_Y	Dominant peak push-off force while feet pushing up or down
DPO_Z	Dominant peak push-off force while feet pushing horizontally, forward or backward
DPO_Z impulse	The area under horizontal force-time curve of the dominant push-off force
EMG	Electromyography
iEMG	Integrated electromyographic signal
iEMGmax	The maximal iEMG
sEMG	Surface electromyography
FINA	Fédération Internationale de Natation
FIR	A finite impulse response

GBST	The Gradient Boosting
ICC	Intraclass correlation coefficient
IQR	Interquartile range
LOOCV	Leave-one-out cross validation
m	Swimmers' body mass
MoCap	Motion capture
MSE	Mean square error
NCAA	The National College Athletic Association
NPO	Non-dominant push-off force
NPO_X	Non-dominant peak push-off force while feet pushing to the left or right force
NPO_Y	Non-dominant peak push-off force while feet pushing up or down
NPO_Z	Non-dominant peak push-off force while feet pushing horizontally forward or backwards
NPO_Z impulse	The area under horizontal force-time curve of the non-dominant push-off force
PCA	Principle component analysis
QRF	The Quantile Random Forest
QTM	Qualisys track manager
R	The coefficient of multiple correlation
R^2	Square of the coefficient of multiple correlation
RF	A random forest algorithm
S	Cross-sectional area
SD	Standard deviation
SL	Stroke length
SR	Stroke rate
SPSS	Statistical package for the social sciences
$TiEMG_{CBRO}$	Total iEMG of core body muscles during rotation
$TiEMG_{CBPO}$	Total iEMG of core body muscles during push-off
$TiEMG_{LLRO}$	Total iEMG of lower limbs muscles during rotation

$TiEMG_{LLPO}$	Total iEMG of lower limbs muscles during push-off
TREE	A single decision tree
TTL	Transistor-transistor logic
v	Velocity
v(t)	Velocity to time curve
V	Volts
VIF	Variance inflation factors
XGBST	The Extreme Gradient Boosting
XTREE	The Extra Trees
ρ	Water density
ω^2	Partial omega squared
2D	Two-dimensional
3D	Three-dimensional

ABSTRACT

Understanding the acquisition of expertise in turning skills from the perspective of a developing young swimmer generally requires the development of a relationship and interaction between characteristics of effective movement and the teaching-learning process. However, few turning biomechanical analyses on age-group swimmers have been conducted to facilitate biomechanical diagnosis and scientific intervention in backstroke to breaststroke turning techniques. The objective of this Thesis were twofold: (i) to identify the biomechanical features that have the greatest influence in each of the four different backstroke to breaststroke turning techniques and (ii) to investigate the effect of four weeks and 16 systematically contextual interference training sessions of 40 minutes each, followed by blocked, serial, and random practice on facilitating learning of the backstroke to breaststroke turning techniques. A multidisciplinary approach, including a motion capture system, a customized underwater tri-axial force plate, surface electromyography (EMG) and an inverse dynamic approach utilizing hydrodynamic variables, was used to accomplish this goal.

We began (in the first study) by identifying the key biomechanical features and determinants of open, somersault, bucket, and crossover turning performance. The electromyographic (EMG) behavior and selected kinematic variables of the four backstroke to breaststroke turning techniques were compared in the second study, with a particular emphasis on rotation and push-off efficacy. The third analysis compared the hydrodynamic characteristics and pull-out strategy related to turn out efficacy. The fourth study employed the linear and tree-based machine learning models to identify the highly realistic models of backstroke to breaststroke turn performance based on comprehensive temporal, kinematic, kinetic (including hydrodynamic) variables. Finally, we looked at how a four-week intervention program that offered systematic increases in contextual interference allows age-group swimmers to improve backstroke to breaststroke turning techniques. Results pointed out that a four-week intervention program improved age-group swimmers' backstroke to breaststroke turning techniques. According to the linear and nonlinear predicted models, optimized turning performance was achieved by a compromise and continuity between the turn-in and turn-out phases. Turn-in efficacy was directly influenced by the contributions of approaching velocity to the wall and rotating abilities in improving rolling velocity and pushing-off force. The integrated electromyographic activity of eight muscles was similar across four turning techniques. The erector spinae and gastrocnemius medialis were the most activated muscles, with the crossover turn having the highest rotation and push-off iEMG values. A comparison of kinetic measures reveals that the bucket turn has a higher peak force, while a higher horizontal impulse leads to higher push-off velocity in the crossover turn. The somersault has a slightly deeper gliding depth, while hydrodynamic characteristics and pull-out strategy, as determinants of turn-out efficacy, did not differ between turning techniques.

KEYWORDS: SWIMMING, AGE-GROUP, BIOMECHANICS, TURNS

RESUMO

Compreender a aquisição de experiência em habilidades de viragens na perspetiva de um jovem nadador em desenvolvimento, geralmente requer o desenvolvimento de uma relação e interação entre as características do movimento efetivo e o processo de ensino-aprendizagem. No entanto, poucas análises biomecânicas de viragens em nadadores de grupos de idade foram conduzidas para facilitar o diagnóstico biomecânico e a intervenção científica em técnicas de viragem nado costas para bruços. Os objetivos desta Tese foram: (1) identificar as características biomecânicas determinantes em cada uma das quatro diferentes técnicas de viragens de nado costas para bruços e (ii) investigar o efeito de 16 treinos de interferência contextuais sistemáticos de 40 minutos cada (quatro semanas), seguido de prática bloqueada, em série e aleatória sobre como facilitar e aprender as técnicas de viragem de nado de costas para nado bruços. Uma abordagem multidisciplinar, incluindo um sistema de captura de movimento, uma plataforma de força tri-axial subaquática personalizada, eletromiografia de superfície (EMG) e uma abordagem dinâmica inversa utilizando variáveis hidrodinâmicas, foi usada para atingir esse objetivo. Começamos (no primeiro estudo) identificando as principais características biomecânicas e determinantes das viragens *open, somersault, bucket* e *crossover*. O comportamento eletromiográfico (EMG) e as variáveis cinemáticas selecionadas das quatro técnicas de viragem foram comparadas no segundo estudo, com ênfase particular na eficácia de rotação e no empurrada da parede. O terceiro estudo comparou as características hidrodinâmicas e a estratégia de arrancamento relacionadas à eficácia fase de saída da viragem. O quarto estudo empregou os modelos de aprendizado de máquina linear e baseado em árvore para identificar os modelos altamente realistas de desempenho das viragens com base em variáveis temporais, cinemáticas e cinéticas abrangentes (incluindo hidrodinâmicas). Finalmente, vimos como um programa de intervenção de quatro semanas que ofereceu aumentos sistemáticos na interferência contextual permite que nadadores de grupos de idade melhorem as técnicas de viragens de nado de costas para nado bruços. Os resultados apontaram que um programa de intervenção de quatro semanas melhorou as técnicas de giro de nado de costas para peito de nadadores de grupos de idade. De acordo com os modelos lineares e não lineares previstos, o desempenho de torneamento otimizado foi alcançado por um compromisso e continuidade entre as fases de entrada e saída das viragens. A eficácia de virada foi diretamente influenciada pelas contribuições da velocidade de aproximação à parede e habilidades de rotação na melhoria da velocidade de rolamento e força de empurrão. A atividade eletromiográfica integrada de oito músculos foi semelhante em quatro variantes de rotação, o eretor da espinha e o gastrocnémio medial foram os mais ativados, com viragem *crossover* tendo os maiores valores de Iemg na rotação e empurre. Uma comparação de medidas cinéticas revela que a viragem *bucket* tem um pico de força mais alto, enquanto um impulso horizontal mais alto leva a uma velocidade de empurre mais alta na viragem *crossover*. A viragem *somersault* apresentou um deslizamento ligeiramente mais profundo, enquanto as características hidrodinâmicas e a estratégia de saída, como determinantes da eficácia da saída na viragem, não diferiram significativamente entre as quatro técnicas de viragem.

PALAVRAS-CHAVE: NATACAO, FAIXAS ETARIA, BIOMECHANICA, VIRAGENS

CHAPTER 1. General Introduction

Swimming performance is a multifactorial phenomenon that has been characterized through the use of deterministic interactions and relationship models between several scientific domains (Morais et al., 2012; Figueiredo et al., 2013). In fact, identifying the morphological, physiological, psychological and technical factors that contribute to swimming performance is one of the main aims of swimming science (Fernandes et al., 2008; Fernandes et al., 2009). Acknowledging that, comprehensive studies focusing on the relative importance of swimming performance determinant and their interaction could provide a deeper understanding of this sport (Pendergast et al., 2006; Figueiredo et al., 2013).

Biomechanical characteristics (including kinematics, kinetics, hydrodynamics, and anthropometrics) are recognized as main overall performance contributors in young swimmers (Morais et al., 2012; Figueiredo et al., 2013), with the interaction of swimming technique and physiological improvement influencing their final performance decisively (Silva et al., 2019; Zacca et al., 2020). Many studies have been focusing on the clean swimming phase, but the contribution of starting, turning and finishing sections to achieve better results in competition is evident (Blanksby et al., 2002). Even if, studies on these topics remain scarce. Specifically, the turning phase plays a significant role in the race final outcome (Prins and Patz, 2006), existing two main turning techniques: the open or pivot turn (used in breaststroke and butterfly events) and the somersault turn (used in freestyle where swimming front crawl, and backstroke events). For changing from backstroke to breaststroke in medley event, swimmers typically use one of four different turning techniques: open turn, somersault (suicide) turn, modified Naber turn (bucket turn) and crossover flip turn (a modification of the old backstroke roll turn) (Figure1).

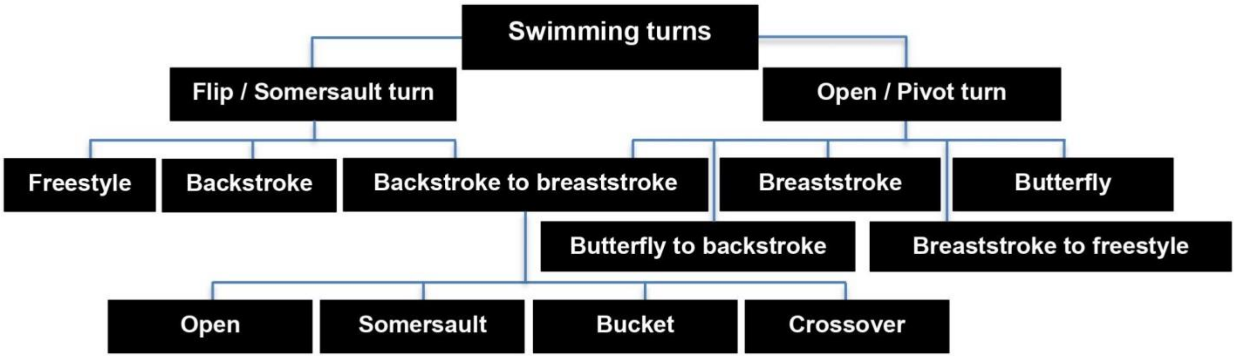

Figure 1. A synthesis of the different turning techniques most commonly used in swimming competitions (adapted from Vilas-Boas and Fernandes, 2003).

The backstroke to breaststroke turn involves multiple factors and require complex specific movements to achieve optimal performance. In fact, depending on the swimmer body position assumed during the rolling and wall contact phases (Figure 2), the backstroke to breaststroke turn can be performed utilizing different techniques (Vilas-Boas and Fernandes, 2003; Lyttle and Blanksby, 2010). The open turn is made by touching the wall in the supine diagonal direction, switching direction on the wall by twisting and rolling onto the side while swinging lower limbs up to the wall and push off the wall on side and rotate from side toward a completed prone streamlined position (Purdy et al., 2012). In the somersault turn, swimmers rotate around a horizontal axis passing through the center of gravity (CG), touches the wall in supine position while pulling lower limbs up, rotating the body around horizontal transverse axis to a semi prone position and push-off and glide with the body positioning towards a complete prone position.

The bucket turns or a modified Naber turn (Vilas-Boas and Fernandes, 2003; Lyttle and Blanksby, 2010) happens when swimmers drive back and touches the wall by reaching back over one shoulder and behind the other shoulder. They spin feet around and bring lower limbs over the water in a tucked position, keeping the back parallel to the bottom of the pool and pushing off the wall in streamline position on side and then rolling to a prone position (Purdy et al., 2012). The crossover or modified roll turn is an integrated turn, in which swimmer takes the last upper limbs backstroke cycle and touch the wall on the swimmer's side by crossing the upper limb over the face to touch the wall (Purdy et al., 2012). Keeping the upper limb outstretched, swimmers (in a tight tuck) pull the lower limbs around to the wall, twist and roll the body on side, continuing to touch the wall. Then, they push-off the wall in streamlined position on side and rolls to a prone position (Vilas-Boas and Fernandes, 2003; Lyttle and Blanksby, 2010; Purdy et al., 2012).

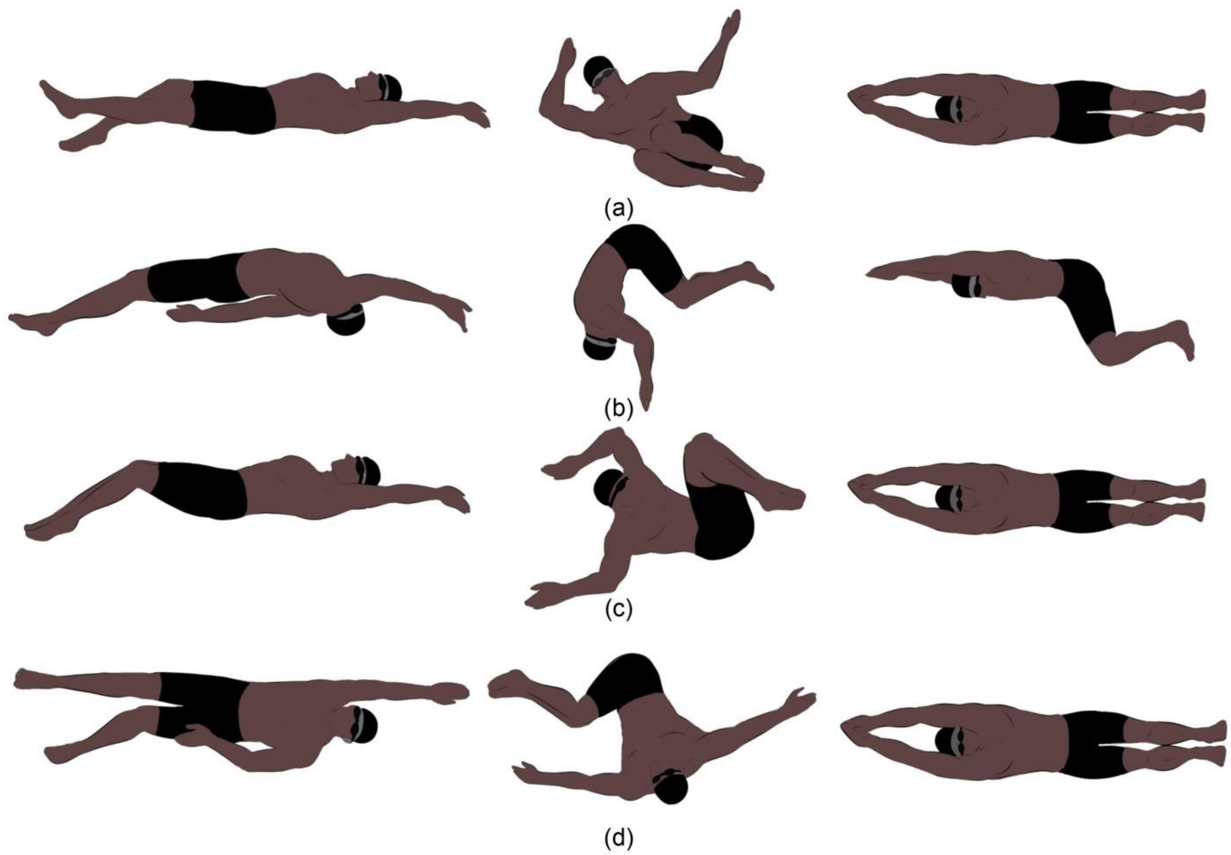

Figure 2. Representation of swimmers body positions during the approach, rotation and push-off phases: (a) open, (b) somersault (c) buckets and (d) crossover turns.

According to a deterministic model (Chow and Knudson, 2011), the total turning backstroke to breaststroke performance is the sum of turn-in and turn-out segments and could be observed within each of five separate phases. Therefore, turning performance can be further decomposed on and can also be determined by the sum of the approach, rolling, wall contact, gliding and pull-out phases (Lyttle and Benjanuvatra, 2004; Webster et al., 2011). The approach phase is usually considered to start when hand enter in 7.5 m to the wall and ends just before the first hand touch in the wall (Blanksby et al., 2004). Regarding the current FINA finishing and individual medley transition rules (SW 6.5 and 9.3), when switching from backstroke to breaststroke is mandatory to touch the wall while on the back, i.e., in supine position (Purdy et al., 2012).

The rotation phase starts at the first hand wall contact, ends before the feet wall contact and is generally divided into two sub-phases: the hand contact (starting with the first hand wall contact and ending on the hand last wall contact; Chollet et al., 2002) and the rotation (starting when the hand leaves the wall and ending on the first feet wall touch; Pereira et al., 2015). The feet wall contact phase starts at the first feet contact to the wall and ends at the instant corresponding to the last feet wall contact. This phase is divided into preparatory and active segment sub-phases: the first starting at the first feet wall contact and ending when the swimmer starts to extend the knees and the second sub-phase starts the push-off phase; Prins and Patz, 2006. Not surprisingly, the influence of biomechanical variables linked to the contact phase on the final push-off velocity has been considered as one of the most critical influencing in flip (Prins and Patz, 2006; Pereira et al., 2015) and rollover backstroke turns (Blanksby et al., 2004).

The turn-out phase is usually considered to start when the feet leave the wall and ends at reaching 15 m out from the wall. From a perspective of turn-out efficacy, turn-out performance results from the combination of the push-off, glide and swimming resumption phases (Prins and Patz, 2006; Naemi, Easson and Sanders, 2010). Theoretically, the gliding phase can be divided into four phases from the push-off from the wall: (i) first gliding; (ii) pull-down or transition phase (the underwater upper and lower limbs actions); (iii) second gliding and (iv) upper and lower limbs recovery, followed by the lower limbs action toward the surface (adapted from Vilas-Boas et al., 2010 and Costa et al., 2015). In addition, the FINA rules for breaststroke swimming turn state that after each turn, swimmers may take one upper limbs action completely back towards the lower limbs at any time prior to the first breaststroke action at the surface and that a single butterfly lower limbs motion is permitted (FINA, 2017-2021, SW 7.1). Consequently, optimizing the glide time and distance, underwater lower limbs action and timing of the pull-out should be taken into consideration since they can significantly affect turn-out time (Lyttle et al., 2000; Vilas-Boas et al., 2010).

Theoretical and practical approaches to understand the expertise of learning skills in age-group swimming is given by an appropriate scheduling intervention and research design (Seifert et al., 2016; Silva et al., 2019) and using accurate and reliable emerging technologies (Vilas-Boas and Fernandes, 2003). Traditional studies of turning techniques in age-group swimmers were focused on identifying the key mechanical variables and the way they predict performance based on modelling the phenomena by linear equations (Blanksby et al., 1998; Blanksby et al., 2004; Ling et al., 2004). Indeed, none researchers have addressed a scheduled intervention program and non-linear analysis, to explain characteristics and dynamics of complex turning movement. For developing technical capability in sports skills, a practice schedule that includes contextual interference has been shown to improve performance and learning expertise (Porter and Magill, 2010; Broadbent et al., 2015) particularly in a continuous sports skill (e.g., swimming, cycling and rowing) (Porter and Beckerman, 2016). Despite this interest, no study has been conducted to apply systematic increasing contextual interference intervention program and non-linear analysis to identify and modeling turning skills, particularly the backstroke to breaststroke in age-group swimmers.

The interpretation of turning performance is uniquely determined by multi-factorial biomechanical variables (Figure 3), using deterministic relationship and interdisciplinary analysis by a novel approach, integrating biomechanical technologies (Pereira et al., 2015; Nicol et al., 2019). Preliminary analysis of turning performance has been focus on the characteristics of the turning time and the relation to total race time in different protocols and standardized distance (Lyttle and Mason, 1997; Chollet et al., 2002). Several fixed distances were then established and employed to analysis, regarding the specific objective and research design, such as 5 m turn time (2.5 m-in + 2.5 m-out; Blanksby et al.,1998; Blanksby et al., 2004), 10 m turn time (5 m-in + 5 m-out; Blanksby et al., 2004; Pereira et al., 2015), 15 m turn time (7.5 m-in + 7.5 m-out; Arellano et al.,1994), 5 m-in and 10 m-out (Mason and Formosa, 2011) and 20 m turn time (5 m-in and 15 m-out; Morais et al., 2019; Marinho et al., 2020).

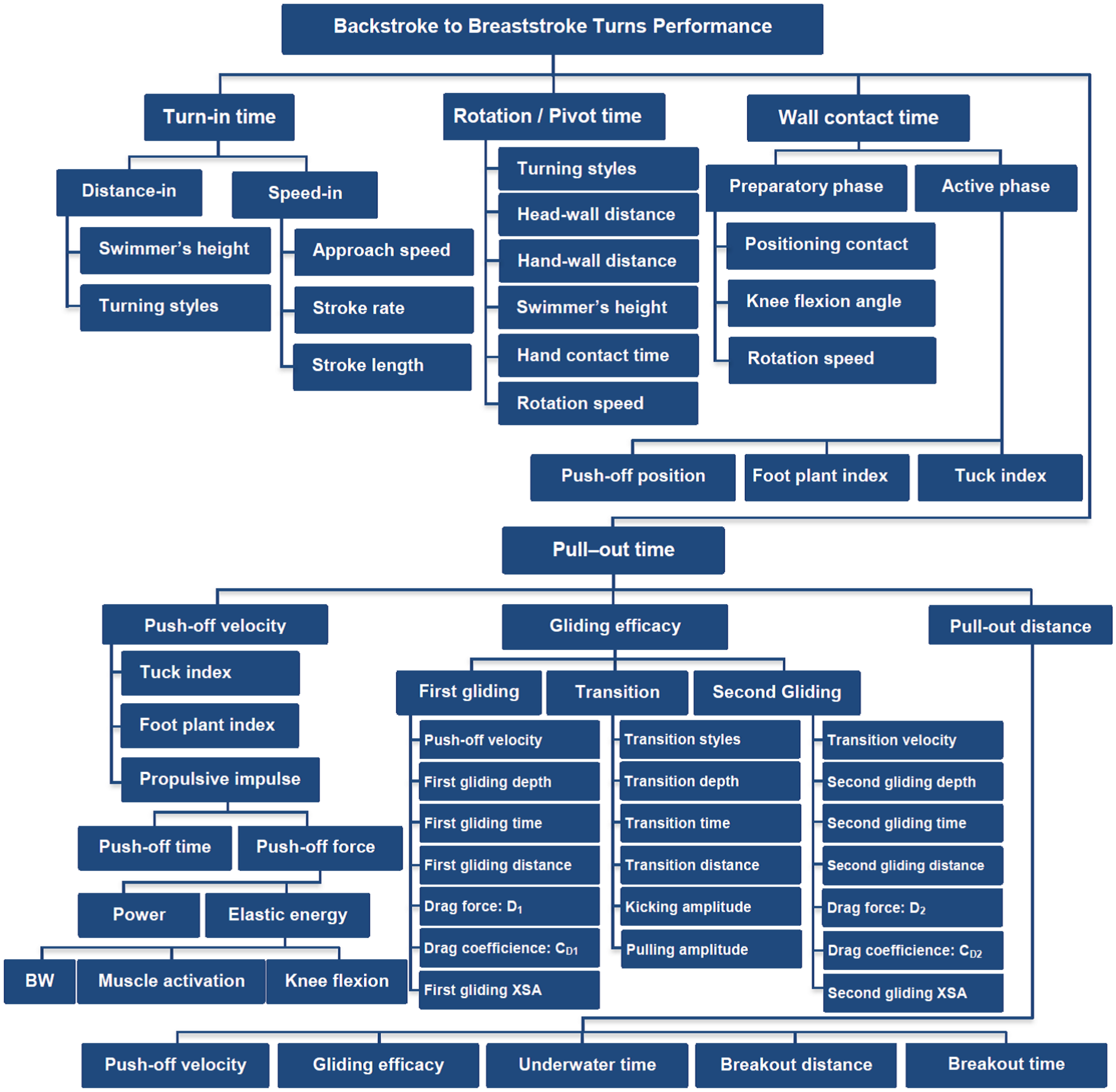

Figure 3. Deterministic model from theoretical and mechanical factors contributing to backstroke to breaststroke turns performance (adapted from Lyttle, 1999; Vilas-Boas and Fernandes, 2003).

In the current Thesis, the 15 m turn time (7.5 m-in + 7.5 m-out) was selected as the criterion and standardized distance for analysis. The 7.5 m-in distance was selected mainly to identify the key biomechanical variables and characteristics of the wall approaching speed, rotational skills and muscular activation of the core and lower limbs during rotation and push-off the wall. The 7.5 m-out distance was selected to monitor the turn-out efficacy throughout the push-off phase, hydrodynamic characteristics and pull-out strategies. In addition the 7.5 m-in + 7.5 m-out was selected to model and predict the total turning performance using linear and non-linear analysis approach.

Previous exploratory studies on the biomechanics of swimming turns have been generally observed based on temporal (Pereira et al., 2015), kinematic (Araujo et al., 2010; Pereira et al., 2015), kinetic (Prins and Patz, 2006; Pereira et al., 2015), EMG (Pereira et al., 2015) and hydrodynamic variables (Vilas-Boas et al., 2010; Marinho et al., 2011). However, relative contribution of the comprehensive biomechanical factors associated with backstroke to breaststroke turn performance have never been determined for conclusively identification of critical elements. Therefore, it is important to identify the most influential biomechanical features of the kinematic-temporal, kinetic, hydrodynamic and electromyography variables that most directly affects to total turning performance in each one of the four studied backstroke to breaststroke turning techniques. Accordingly, the most determinant biomechanical factors that contribute to turning performance using linear and non-linear regression should be specifically addressed.

The current Chapter – General Introduction – contextualizes the theoretical assumptions regarding the characteristics of the four backstroke to breaststroke turns, research design using novel biomechanical technologies and systematically contextual interference training programme. Chapters 2 to 6 present the experimental accomplishments of the current Doctoral Thesis. General discussion (Chapter 7) was elaborated upon the results obtained from those studies, supported by the specialized literature. Chapters 8, 9 and 10, present the main conclusion, suggestions for future research and references, respectively.

According to literature and scientific evidence, the improvement in young swimming performance appears to be strongly related to technical training enhancement by increasing technical efficacy and optimizing hydrodynamic characteristics (Morais et al., 2012; Fernandes et al., 2011; Silva et al., 2019). In swimming turns performed by age-group swimmers, most of the studies tended to focus on the kinematic-temporal and kinetic characteristics to identify key mechanical features contribution in each phase and related to the total turning performance (Blanksby, Gathercole and Marshall, 1996; Blanksby et al., 1998; Blanksby et al., 2004; Ling et al., 2004). However, swimming turn performance is highly dependent on their turn-in and and turn-out efficacy (Prins and Patz, 2006; Naemi, Easson and Sanders, 2010; Nicol et al., 2019) and turn-out efficacy is mostly associated with an optimization of the hydrodynamic performance (Blanksby et al., 1998; Naemi, Easson and Sanders, 2010). Thus, understanding characteristics of the gliding position and the pull-out strategy would afford swimmers and coaches an insight into the influence of an interaction of hydrodynamic parameters with the other biomechanical determinant factors (i.e., kinematics-temporal and kinetics) to the total turning performance.

As so, an appropriate monitoring using emerging technologies and scientific reasoning is necessary to accurately understand the relationship between the key kinematic-temporal, kinetic and hydrodynamic variables on total turning performance. The aim of our first experiment was to identify key biomechanical features of the four studied different backstroke to breaststroke turning techniques (open, somersault, bucket and crossover) in age-group swimmers (**Chapter 2**). For that purpose, a protocol was implemented through 3D dual-media automatic tracking, two tri-axial underwater force plates and hydrodynamic variables assessed through inverse dynamics.

Existing understanding of swimming turns has typically characterized biomechanical aspects and elements that contribute to performance throughout the approach, rotation, wall-contact, glide, and stroke preparation phases (Blanksby et al., 2004; Slawson et al., 2010; Pereira et al., 2015). Identifying the key characteristics of kinematic-temporal, kinetic and hydrodynamic variables that influence rotation and wall push-off efficacy might provide valuable insight into optimal movement strategies when evaluating turning variations differentiated by altered body rotation (Blanksby et al., 2004; Araujo et al., 2010; Pereira et al., 2015). However, the current knowledge remains incomplete in delineation of the role of neuromuscular activation, particularly the lower limbs and core muscles during rotation and push-off phases when considering different turning techniques (Pereira et al., 2015).

The use of surface electromyography (sEMG) provides valuable information allowing for a better understanding of swimming technical actions (Clarys and Rouard, 2011; Figueiredo et al., 2013; de Jesus et al., 2015) and specific muscles involved in movement (Clarys, 1983; Clarys and Cabri, 1993). Knowing this, our second experimental study aimed to determine and compare the EMG activity levels among four types of backstroke to breaststroke techniques and observe eventual relationships between iEMG and selected kinematic variables related with rotation and push-off efficacy (**Chapter 3**). It was hypothesized that the EMG response of relevant lower limb and core muscles during the rotation and push-off phases would be sensitive to the different backstroke to breaststroke turning techniques. Together with the **Chapter 2**, findings would allow a holistic approach to identify the complex interaction of interdisciplinary factors involving the kinematic-temporal, kinetic, hydrodynamic and electromyographic variables that influence turning performance. Identifying the role of biomechanics and neuromuscular variables in producing a faster rotation and maximum push-off force and impulse would provide a better understanding of the interaction between rotation and push-off phase to optimize overall backstroke to breaststroke turns performance.

Previous swimming turn related studies revealed that total turning performance is highly associated with faster approach and rotation, in conjunction with an optimization of the wall contact phase and turn-out efficacy, throughout gliding and swimming resumption phases (Blanksby et al., 2004; Naemi, Easson and Sanders, 2010; Vilas-Boas et al., 2010; Pereira et al., 2015; Nicol et al., 2019). Current understanding of total turn performance in age-group swimmers has come mostly from statistical modeling and predicting the relationships between a dependent variable of wall contact and turn-out phase on turn-out and total turning performance (Blanksby, Gathercole and Marshall, 1996; Blanksby et al., 1998; Blanksby et al., 2004; Ling et al., 2004). Theoretically, identifying key mechanical variables for turn-out efficacy results from the optimum peak forces to generate impulses and push-off velocity (Blanksby et al., 2004; Araujo et al., 2010; Pereira et al., 2015), properly streamlined posture (Havriluk, 2005; Lyttle and Benjanuvat, 2006; Naemi, Easson and Sanders, 2010) and optimal underwater gliding and breakout distance (Blanksby et al., 2004; Nicol et al., 2019). A greater understanding of these wall contact and turn-out relationships would enable identification of preferred pull-out strategy and determination of the most efficient turning technique. However, much aforementioned work on the potential of turn-out efficacy on turning performance has been carried out in freestyle, breaststroke, backstroke and butterfly turns, there are still many critical issues in the backstroke to breaststroke turns. Therefore, in **Chapter 4,** we purposed to compare hydrodynamic characteristics and pull-out strategy on turn-out performance of the four studied backstroke to breaststroke turning techniques in age-group swimmers.

In fact, the identification of variables that can be used to predict swimming performance is one of the main topics in swimming science (Costa et al., 2012) and in **Chapter 2** and **Chapter 3** previous approach. Since swimming performance is a multifactorial phenomenon, theoretical and statistical models have been developed to explain the interaction and contribution of biomechanical variables related to swimming performance (Barbosa et al., 2010; Figueiredo et al., 2013). Linear regression analysis is the most widely and commonly used statistical technique to investigate the relationship of biomechanic variables associated with start performance (de Jesus et al., 2011; Tor, Pease and Ball, 2015) and total turning performance (Blanksby et al., 1998; Blanksby et al., 2004; Ling et al., 2004). However, the interrelations between competitive performance variables are not always linear relationships between independent variables and a dependent one (Edelmann-Nusser, Hohmann and Henneberg, 2002; de Jesus et al., 2018).

The accuracy of using linear and non-linear regression models to predict the relative contributions of each factor associated with swimming performance has been addressed in front crawl swimming (Heazlewood, 2006; Stanula et al., 2012) and backstroke start performance (de Jesus et al., 2018). This approach has not been previously studied using machine learning algorithms with difference cross-validation for modeling and predicting backstroke to breaststroke turning performance. Therefore, we have conducted another original study (**Chapter 5**) that aimed to: (i) identify the biomechanical variables associated with 15 m turning performance while performing the backstroke to breaststroke turning techniques, such as the open, somersault, bucket, and crossover;

and (ii) to predict 15 m turning performance that was summarized from the 7.5 m turn-in and 7.5 m turn-out distances, using linear regression and tree-based machine learning models from selected kinematic-temporal, kinetic and hydrodynamic variables.

Swimming performance is mainly determined by the interaction of physical, technical and psychological abilities by a precisely controlled training program (Mujika et al., 1996), with the turning techniques being a central concern along the process, particularly in young swimmers (Barbosa et al., 2010). In addition, instructional turning techniques program need to create specific objectives that swimmer should accomplish. Therefore, some researchers suggested to follow-up the swimmers performance and its determinant factors using longitudinal or training-intervention designs (Costa et al., 2015; Silva et al., 2019; Zacca et al., 2020). Training-interventions allow tracking down swimmer’s performance and its determinant factors, defining realistic goals and training methods during a full competitive season (Costa et al., 2012; Morais et al., 2013). Regarding the swimming start, an intervention training program has been conducted along 14 ± 2 sessions in elite swimmers (Blanksby et al., 2002) and four-week intervention (Galbraith et al., 2008) in elite age-group swimmers. Notwithstanding, no research has attempted to analyse an intervention training program on turning performance, particularly in age-group swimmers.

Contextual interference is defined as the interference in performance and learning that arises from practicing one task in the context of other tasks (Porter and Magill, 2010). Characteristics of schedule became progressively more challenging by progressing to serial and later random scheduling, the learners were able to manage the difficulties of the elevated contextual interference because of more efficient information processing abilities and a more evolved motor program (Porter and Magill, 2010; Porter and Beckerman, 2016). Previous studies revealed that a practice schedule offering systematic increases in contextual interference have been very promising for learning sports skills (Porter and Magill, 2010; Broadbent et al., 2015; Buszard et al., 2017), particularly in the cyclic and complex skills (Porter and Magill, 2010; Porter and Beckerman, 2016). Despite this interest, no one, to the best of our knowledge, has been conducted to offer systematic increases in contextual interference for investigating turning performance. In this sense, it was aimed to examine biomechanical characteristics of the four different backstroke to breaststroke turning techniques following a four-week contextual interference programme in age-group swimmers (**Chapter 6**).

In summary, the purpose of this Thesis was to understand the kinematic-temporal, kinetic, electromyographic and hydrodynamic features that have the greatest influence in each of the four different backstroke to breaststroke turning techniques through using 16 systematically contextual interference training sessions to facilitate learning skills. This thesis intended to take a multidisciplinary approach to studying age-group backstroke to breaststroke turning, including the use of comprehensive biomechanics devices, optimizing the teaching-learning process, combining aspects of performance analysis and utilizing data mining and machine learning to improve our understanding of turning performance.

CHAPTER 2.

Biomechanical features of backstroke to breaststroke transition techniques in 11-13 years old age-group swimmers

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Abstract

The aim of this study was to identify the biomechanical features of backstroke to breaststroke transition techniques (*open*, *somersault*, *bucket* and *crossover*) in age-group swimmers. Eighteen pre-adolescent swimmers (12.2 ± 0.4 years old and 3-4 Tanner stages) underwent four weeks systematic contextual interference training, comprising 16 sessions (40 min·session^{-1}). Soon after, an experimental testing was conducted where swimmers randomly performed 12 x 15-m maximal turns (composed by 7.5 m turn-in and 7.5 m turn-out of the wall segments), three in each transition technique. Kinematical, kinetic and hydrodynamic variables were assessed with dual-media motion capture system (12 land and 11 underwater cameras), tri-axial underwater force plates and inverse dynamics. Variables were grouped in turn-in (approach and rotation) and turn-out (wall contact, gliding and pull-out) phases, with factor analysis used to select the variables entering on multiple regressions. For the turn-in phase, 86, 77, 89 and 87% of variance for *open, somersault*, *bucket* and *crossover* turning techniques (respectively) was accounted by the 7.5 and 2.5 m times, mean stroke length and rotation time. For the turn-out phase, first gliding distance and time, second gliding depth, turn-out time, and dominating peak_Z push-off force accounted for 93 % in open turn, while wall contact time, first gliding distance, breakout distance and time, turn-out time, dominating peak_Y push-off force, and second gliding drag coefficient accounted for 92 % in a somersault turn. The foot plant index, push - off velocity, second gliding distance and turn-out time accounted for 92% in bucket turn while breakout and turn-out time, non-dominating peak_Y and peak_Z push-off force, first and second gliding drag force and second gliding drag coefficient accounted for 90 % in crossover turn, respectively. The findings in this study were novel and provide relevant biomechanical contribution, focusing on the key kinematic–temporal determinant during turn-in, rotation, and push-off efficacy, as well as the kinetic and hydrodynamic during turn-out, which would lead to improved backstroke to breaststroke transition techniques in 11–13-year-old age-group swimmers.

Key words: motion capture; force plate; hydrodynamic; turn technique; swimming

Abbreviations	
a	Mean acceleration for each gliding
B	Unstandardized beta
C_D	Drag coefficient
C_{D1}	Drag coefficient of the first gliding position
C_{D2}	Drag coefficient of the second gliding position
Cp	Total square error
D	Drag force
D_1	Drag force of the first gliding position
D_2	Drag force of the second gliding position
DPO	Dominant push-off force
DPO_X	Dominant peak push-off force while feet pushing to the left or right
DPO_Y	Dominant peak push-off force while feet pushing up or down
DPO_Z	Dominant peak push-off force while feet pushing horizontally
DPO_Z impulse	The area under horizontal force-time curve of the dominant push-off force
NPO	Non-dominant push-off force
NPO_X	Non-dominant peak push-off force while feet pushing to the left or
NPO_Y	Non-dominant peak push-off force while feet pushing up or down
NPO_Z	Non-dominant peak push-off force while feet horizontal pushing
NPO_Z impulse	The area under horizontal force-time curve of the non-dominant push -off force
R	The coefficient of multiple correlation
R^2	Square of the coefficient of multiple correlation
S	Cross-sectional area
SL	Stroke length
TTL	Transistor-transistor logic
v	Velocity
v(t)	Velocity to time curve
V	Volts
VIF	Variance inflation factors
ρ	Water density

Introduction

Performing fast and skilled turning actions, as well as start and swim phases, is fundamental for improving competitive swimming performance (Arellano et al., 1994; McGibbon et al., 2018). However, conclusive information on the 200- and 400-m individual medley events, in which butterfly, backstroke, breaststroke, and freestyle are swum in this order, is limited. Therefore, extensive research is required to identify the key biomechanical variables and their respective contributions to each transition technique (Chainok et al., 2021).

Among the medley turns, there are four well-described backstroke to breaststroke transition techniques (the *open*, the *somersault*, the *bucket* and the *crossover*) which are very complex movements (*i.e.,* performed in different planes and axes). Additionally, swimmers need to comply with the FINA rules, *i.e.*, touch the wall while on their back, maintaining the shoulders at or past the vertical direction toward the breast when leaving the wall and assuming a ventral gliding position prior to the first breaststroke upper limbs action. Studies on the backstroke to breaststroke transition techniques are scarce, lacking scientific and practical validation of the specific determinant factors that play a vital role in gaining advantage in each backstroke to breaststroke transition techniques.

Key biomechanical variables related to swimming turn performance have been studied using temporal, kinematic (Blanksby et al., 2004; Araujo et al., 2010; Pereira et al., 2015), kinetic (Prins and Patz, 2006; Pereira et al., 2015; Chainok et al., 2021) and hydrodynamic data (Benjanuvatra, Blanksby and Elliott, 2001; Vilas-Boas et al., 2010; Chainok et al., 2021), but no study has examined the biomechanical determinants for optimal backstroke to breaststroke transition performance. Knowing that this information is a key factor for coaches when planning their specific training activities, we aimed to identify the key biomechanical variables that affect the performance in the four backstroke to breaststroke transition techniques in age-group swimmers. It was hypothesized that the 15 m turning time performance is described by combining contributions from the turn-in and turn-out phases, as well as different combinations of feature variables depending on the chosen backstroke to breaststroke transition technique.

Materials and methods

Subjects

Eighteen age-group swimmers, nine boys and nine girls, from the 11-13 years old age-group of a competitive swimming club, volunteered to participate in the current study. Boys and girls characteristics were (respectively): 12.5 ± 0.5 *vs.* 11.6 ± 0.5 years old, 48.7 ± 12.4 *vs.* 46.7 ± 10.8 kg of body mass, 1.59 ± 0.14 *vs.* 1.52 ± 0.07 m of height, 14.8 ± 5.1 *vs.* 21.8 ± 7.10% of fat mass, 3-4 Tanner stages and 59 ± 9 *vs.* 55 ± 12% of 200 m individual medley best performances of the 2018 short-course World Junior Record. Swimmers parents were informed about the benefits and risks of participating before they were asked to sign an informed-consent form (approved by the ethics board of the local university - CEFADE 08.2014) in agreement with the Declaration of Helsinki.

Procedures

Four backstroke to breaststroke transition techniques were identified (FINA rules; https://www.fina.org/, see **Figure 1**). Prior to the experiments, swimmers answered a questionnaire about their backstroke to breaststroke transition techniques preferences, with 18 selecting the open technique and only two the somersault. The experimental protocol took place in a 25-m (1.90 m deep) indoor pool with ~ 27 and ~ 26ºC of water and air temperatures (respectively) and 59% relative humidity. Age-group swimmers joined 16 practice sessions throughout a four-weeks training program (see details in Chainok et al., 2021) performing variants of the same task with structured increases in contextual interference (Porter and Magill, 2010). Contextual interference can be defined as the interference in performance and learning that arises from practicing one task in the context of other tasks (Schmidt and Lee, 2005; Porter and Magill, 2010). The 16 practice sessions were part of the regular training sessions, with the turning practice occurring during the last 40 min of every session. Two experienced coaches conducted all practice sessions and specific coaching feedback based on mechanical factors to ensure consistency in coaching techniques, proper familiarization, (de Jesus et al., 2016; Galbraith et al., 2008). All participants followed a schedule program from the 1st to the 16th practice session program (see details in Chainok et al., 2021). At the end of the intervention period, swimmers were invited for an evaluation session. Thus, after a 400-

m moderate intensity warm-up including some elements of backstroke to breaststroke transition techniques (Figure 1), swimmers were invited to perform 12 x 15-m maximal turns (composed by 7.5 m turn-in and 7.5 m turn-out of the wall segments). Each swimmer completed three attempts of each backstroke to breaststroke transition technique (randomized order), with a 3 min rest interval between trials (see details in Chainok et al., 2021).

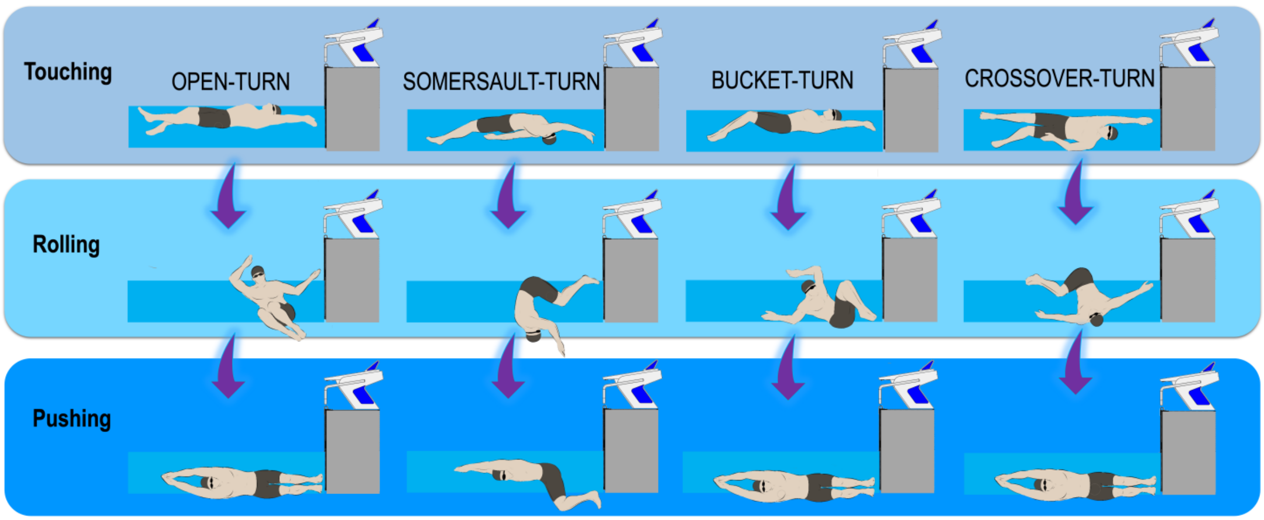

Figure 1. Backstroke to breaststroke turning techniques are distinguished by the different body orientations of the swimmers throughout the touching rolling and pushing-off phases.

Dual-media motion capture system with 12 land and 11 underwater cameras (Oqus 3 and 4 series, Qualisys, Gothenburg, Sweden) and a full-body marker setup (with 51 spherical retro-reflective markers, see **Figure 2**) were used to track swimmer´s actions at 100 Hz (Lauer et al., 2016) (see details of camera placement and configuration and calibration in Chainok et al., 2021). The kinetic assessment was obtained with two tri-axial underwater force plates (Mourão et al., 2016) operating at a 2000 Hz sampling frequency and fixed into the pool's wall on a custom-built support (see details in de Jesus et al., 2019). The limits of this structure were identified with four retroreflective markers.

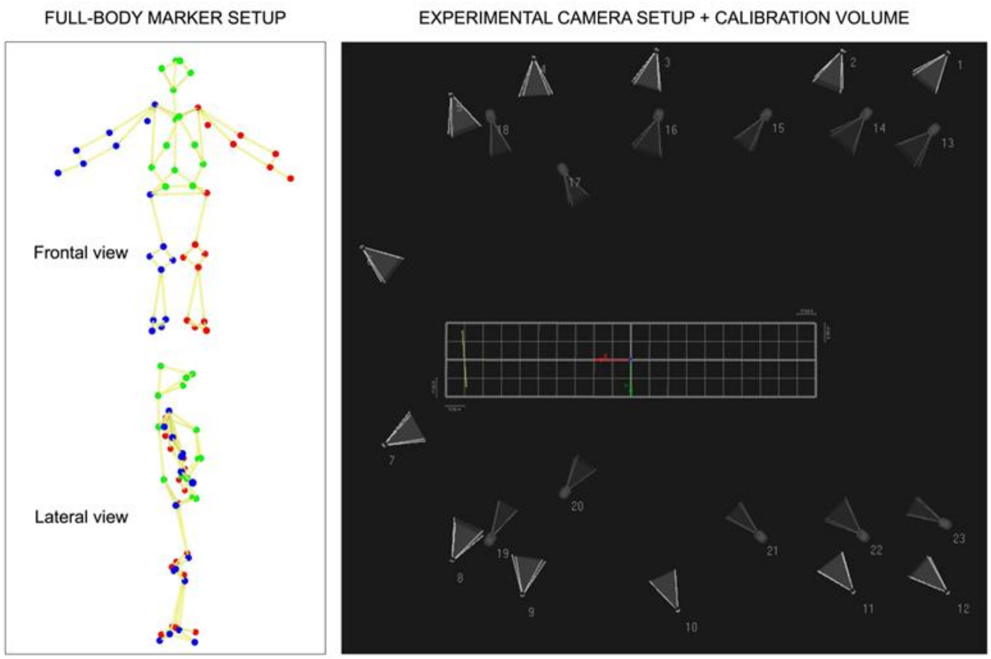

Figure 2. Configuration of kinematic-temporal data: full-body marker setup in Qualisys Track, experimental camera positioning with 12 land and 11 underwater cameras, and calibration volume covered. The orthogonal axes were defined as X, Y and Z for horizontal, medio-lateral, and vertical (Z = 0 defines water surface) movements.The yellow rectangle depicts the reference system and positioning of the tri-axial two force platforms.

The 15 m turning time performance (composed by 7.5 m turn-in and 7.5 m turn-out of the wall segments) encompassed approaching, touching (wall contact), rolling, pushing glide and swimming resumption until the vertex passes the 7.5 m marker (**Figure 1**). The Qualisys Track Manager (Oqus 3 and 4 series, Qualisys, Gothenburg, Sweden) software was used to acquire the temporal and 3D kinematic data. Built-in spline interpolation was used to fill markers' missing trajectories (representing up to ~50, 120 and 60 frames, *i.e.*, 3.3, 8.0 and 4.0% of the trial duration in the approach, rotation, and turnout phases, respectively). The software Acqknowledge v.3.9.0 (BIOPAC Systems Inc., Santa Barbara, CA, USA) was used to perform residual analysis to optimize the digital filter cut-off frequency (fast Fourier transform) and kinematic–temporal data were low-pass filtered using a digital filter with a cut-off frequency of 6 Hz (FIR – Window

Blackman-61dB) (Acqknowledge, BIOPACiopac Systems, Inc., Santa Barbara, CA, USA). The bow wave effect at the beginning of the feet contact was considered negligible (not edited in the kinetic analysis) since swimmers glided in before touching the wall and rotated to push-off.

Despite that, the underwater force platforms were synchronized with the motion capture system and the image-based kinematics allowed a reasonable verification of the force-to-time curve symmetry. Dominant (DPO) and non-dominant (NPO) push-off force terms were used to identify the characteristic peak force contributions in the x, y and z components. Kinetic data processing was divided in: (i) acquisition, plotting and saving the strain readings of each tri-axial force and the moment-of-force components from each force plate using a custom LabVIEW™ program (National Instruments, Austin, TX, USA, http://www.ni.com/en-us/shop/labview.html) (Mourão et al., 2016; de Jesus et al., 2019); (ii) converting the strain readings into force values according to the previous calibration (Matlab R2014a, MathWork Inc., Natick, MA, USA) and (iii) filtering curves using a 4th-order zero-phase digital Butterworth filter with a 10 Hz cut-off frequency (Mourão et al., 2016; de Jesus et al., 2019) (**Figure 3**). The hydrodynamic variables (drag, drag coefficient and body cross-sectional area) were assessed through inverse dynamics approach (Vilas-Boas et al., 2010). We used planimetry (Clarys,1979; Vilas-Boas et al., 2010) for cross-sectional area (S) assessment. (**Figure 4**; see details in Chainok et al., 2021). The description of the studied kinematic–temporal, kinetic and hydrodynamic variables are accessible at **Table 1 and Table 2**.

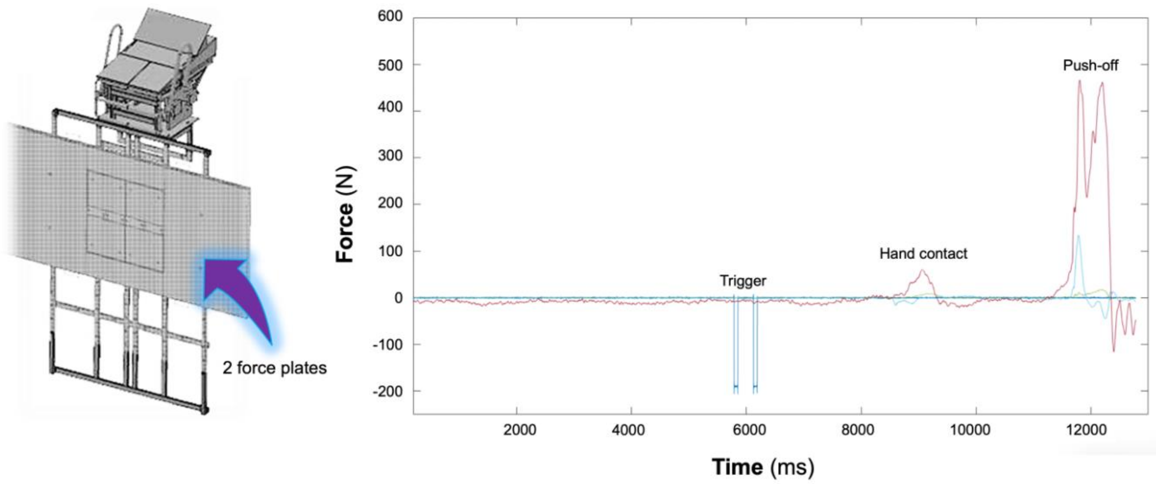

Figure 3. Kinetic data set up and data processing: two tri-axial force plates set up and force-time curve of two tri-axial force plate profiles (left and right panels). Fx and Fy are the medio-lateral (green) and up and down (blue) components, and Fz is the horizontal force component (red).

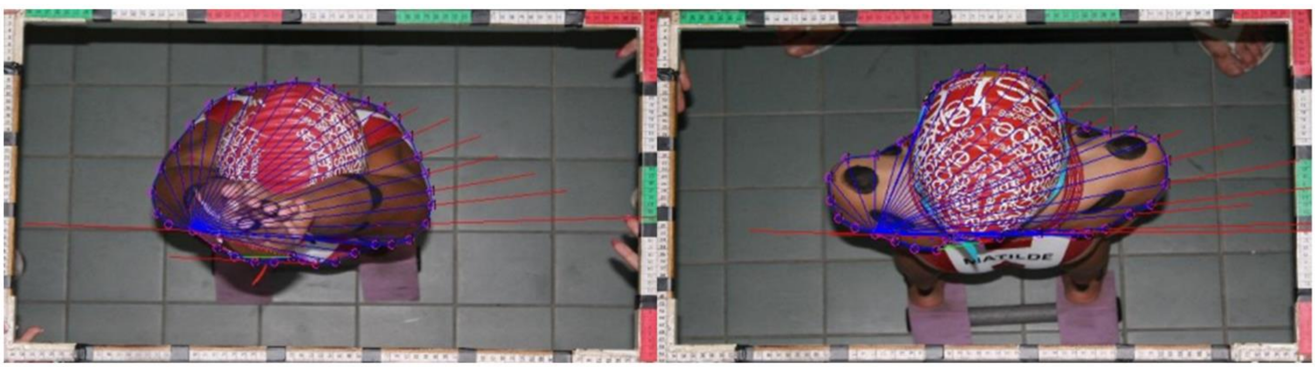

Figure 4. Body surface area determined through planimetry: data processing of the first and second gliding position.

Table 1. Kinematic-temporal variables selected for studying backstroke to breaststroke turning techniques.

Variables	Definition
7.5 m time-in (s)	Time between vertex reached 7.5 m wall distance at an origin of referential system until the hand wall touch.
5 m time-in (s)	Time between vertex reached 5 m wall distance at an origin of referential system until the hand wall touch.
2.5 m time-in (s)	Time between vertex reached 2.5 m wall distance at an origin of referential system until the hand wall touch.
Last upper limbs -wall	Middle finger to wall distance at the last upper limbs cycle.
SL at last cycle (m)	The last upper limbs cycle length that was obtained by the horizontal displacement of the one upper limbs cycle.
Average SL during turn-in (m)	The mean of the last five upper limbs cycle length that was obtained by the horizontal displacement of the one upper limbs cycle.
Touching depth (m)	Depth at the hand beginning wall touch.
Hand contact time (s)	Time at hand wall contact.
Rotation time (s)	Time between hand contacts to feet contact.
Total wall contact time (s)	Total contact time of the feet with the wall.
Push-off time (s)	Time spent with the feet against the wall as the hips moved forward until the feet exited the wall.
Tuck index	The distance between the right hip and the wall at the start of the push-off is divided by the swimmer's lower limb.
Foot plant index	Depth of the wall foot plant at the beginning of push-off divided by swimmer's lower limb.
Push-off velocity ($m \cdot s^{-1}$)	Resultant velocity of sacrum at the feet had left the wall.
First gliding distance (m)	Distance of sacrum travel from the feet had left the wall to the first frame of transition phase.
First gliding time (s)	Time of sacrum travel from the beginning of feet had left the wall to the first frame of transition.
First gliding depth (m)	Mean of sacrum depth during the gliding phase.
Transition distance (m)	Distance of sacrum travel from the initial separation of the hands or starting dolphin kick until upper limbs fully extended at sides of the
Transition time (s)	Time of sacrum travel from the initial of hands separate or starting dolphin kick until the upper limbs fully extended at sides of the body.
Transition gliding depth (m)	Mean of sacrum depth during transition phase.
Second gliding distance (m)	Distance of sacrum travel from the first frame of the upper limbs fully extended at sides of the body to an instant which hands begins to
Second gliding time (s)	Time of sacrum travel from the first frame of the upper limbs fully extended at the sides of the body to an instant which hands begins to
Second gliding depth (m)	Mean of sacrum depth during the second gliding phase.
Breakout distance (m)	Distance at which the head breaks the surface for the first time.
Breakout time (s)	Time from the feet had left the wall to the vertex breaks the surface for the first time.
Time-out (s)	Time from the feet had left the wall to the vertex reach 7.5 m mark.
15 m turn time (s)	The turn time performance including 7.5 m time-in and 7.5 m time-out.

Table 2. Kinetic and hydrodynamic variables selected for analyzing the backstroke to breaststroke turns.

Variables	Definition
Hand peak X force (N)	The highest force applied while hand pushing to the left or right on the force plate during hand contact.
Hand peak Y force (N)	The highest force applied while hand pushing up or down on the force plate during hand contact.
Hand peak Z force (N)	The highest force applied perpendicular to the force plate during hand contact.
Hand contact impulse (Z) (Ns.)	The area under the perpendicular Z force-time curve during hand contact.
Non-dominant peak_X push-off	The highest force applied while feet pushing to the left or right on the non-dominant force plate to the feet had left the wall.
Non-dominant peak_Y push-off	The highest force applied while feet pushing up or down on the non-dominant force plate during to the feet had left the wall.
Non-dominant peak_Z push-off	The highest force applied while feet horizontal pushing on the non-dominant force plate to the feet had left the wall.
Non-dominant push-off impulse	The area under the Z force-time curve during the foot push-off non-dominant force plate to the feet had left the wall.
Dominant peak_X push-off force : DPO_X (N)	The highest force applied while feet pushing to the left or right on the dominant force plate to the feet had left the wall.
Dominant peak_Y push-off force : DPO_Y (N)	The highest force applied while feet pushing up or down on the dominant force plate during to the feet had left the wall.
Dominant peak_Z push-off force : DPO_Z (N)	The highest force applied while feet horizontal pushing on the dominant force plate to the feet had left the wall.
Dominant push-off impulse (Z) (Ns)	The area under the Z force-time curve during the foot push-off dominant force plate to the feet had left the wall.
First gliding drag force (N)	The passive drag force during the first gliding position that was assessed through inverse dynamics (D = ma).
Second gliding drag force (N)	The passive drag force during the second gliding position that was assessed through inverse dynamics (D = ma).
First gliding drag coefficient	The drag coefficient during the second gliding position that was assessed through inverse dynamics, following equation ($C_D = 2D / \rho S v^2$).
Second gliding drag coefficient	The drag coefficient during the second gliding position that was assessed through inverse dynamics, following equation ($C_D = 2D / \rho S v^2$).

Statistical analysis

Basic exploratory and descriptive statistics were computed using SPSS Statistics for Windows Version 24.0 (IBM Corp., Armonk, NY, USA) aiming to detect potential errors in data entry and eventual outliers, as well as assessing data distribution normality (Shapiro-Wilk test), multicollinearity (variance inflation factors) and homoscedasticity (Levene's test). A one-way analysis of variance (ANOVA) was used to observe differences in the selected kinematic–temporal, kinetic and hydrodynamic variables among the four different backstroke to breaststroke turning techniques. If a significant effect was found, post hoc pairwise comparisons using Tukey's HSD were conducted. Then, a factor analysis was conducted to lower the number of variables and to analyze the relationships structures between variables. For this purpose, selected variables were grouped into turn-in and-out variables (approach and rotation vs wall contact, gliding and pull-out phases), factors were chosen on the basis of a cut-off Eigen value of 1, principal component extraction with a varimax rotation and the scree plot proposed (Tor, Pease and Ball, 2015), and best-subsets analysis was conducted to determine the best regression equation for 15 m turn time prediction (using Minitab 19, Minitab Inc., State College, PA, USA). Finally, a multiple regression analysis (with the enter method) was used to determine and predict the 15 m turn time based on each turning technique selected variables. The full multiple linear regression analysis was completed with SPSS based on the largest R^2 value and the smallest error.

Results

Descriptive and variance related analysis on selected variables for each backstroke to breaststroke turning technique are presented in **Table 3**. The turning techniques showed no significant effects on the turn-in ($F_{3, 232} = 0.61$; $p = 0.61$), rotation time ($F_{3, 232} = 0.69$; $p = 0.56$), turn-out ($F_{3, 232} = 0.33$; $p = 0.80$) and 15 m turn times ($F_{3, 232} = 0.64$; $p = 0.59$).

Table 3. Descriptive and variance related statistics of the studied variables.

Variables	Open	Somersault	Bucket	Crossover	Total
7.5 m time-in (s)	7.42 ± 0.63	7.35 ± 0.55	7.30 ± 0.65	7.45 ± 0.70	7.38 ± 0.63
5.0 m time-in (s)	5.20 ± 0.54	5.15 ± 0.47	5.12 ± 0.59	5.21 ± 0.61	5.17 ± 0.55
2.5 m time-in (s)	2.48 ± 0.32	2.45 ± 0.29	2.52 ± 0.36	2.48 ± 0.34	2.48 ± 0.33
Last upper limbs-wall distance	0.45 ± 0.25[s]	0.57 ± 0.25[o]	0.52 ± 0.25	0.48 ± 0.27	0.51 ± 0.26
SL at last cycle (m)	1.63 ± 0.28	1.55 ± 0.28	1.64 ± 0.31	1.63 ± 0.33	1.61 ± 0.30
Average SL during turn-in (m)	1.68 ± 0.20	1.65 ± 0.18	1.71 ± 0.21	1.70 ± 0.20	1.69 ± 0.20
Touching depth (m)	0.18 ± 0.09[s]	0.36 ± 0.13[o,b,c]	0.16 ± 0.09[s]	0.13 ± 0.06[s]	0.21 ± 0.13
Hand contact time (s)	0.49 ± 0.21[b,c]	0.49 ± 0.18[b,c]	0.59 ± 0.15[o,s,c]	0.37 ± 0.16[o,s,b]	0.48 ± 0.19
Hand peak X force (N)	1.59 ± 0.32	1.61 ± 0.23[c]	1.68 ± 0.26[c]	1.50 ± 0.23[s,b]	1.60 ± 0.27
Hand peak Y force (N)	8.56 ± 1.62[b]	8.48 ± 1.09[b]	17.37 ± 3.18[o,s,c]	9.05 ± 1.72[b]	10.78 ± 4.32
Hand peak Z force (N)	24.67 ± 29.47[s]	42.58 ± 51.80[o,c]	41.86 ± 52.89[c]	21.89 ± 26.11[s,b]	32.88 ± 12.85
Hand contact impulse (Z) (Ns.)	14.77 ± 3.19[s,b]	23.40 ± 4.41[o,c]	24.82 ± 5.03[o,c]	8.65 ± 1.53[s,b]	17.63 ± 7.25
Rotation time (s)	1.24 ± 0.18	1.28 ± 0.24	1.31 ± 0.27	1.33 ± 0.24	1.29 ± 0.23
Total wall contact time (s)	0.57 ± 0.19	0.54 ± 0.12[c]	0.53 ± 0.12[c]	0.63 ± 0.18[s,b]	0.57 ± 0.16
Push-off time (s)	0.38 ± 0.16	0.43 ± 0.13	0.37 ± 0.09[c]	0.46 ± 0.14[b]	0.41 ± 0.14
Tuck index	0.70 ± 0.15	0.75 ± 0.11	0.76 ± 0.10	0.72 ± 0.13	0.73 ± 0.13
Foot plant index	0.58 ± 0.19[s,c]	0.68 ± 0.19[o,b,c]	0.55 ± 0.18[s]	0.50 ± 0.15[o,s]	0.58 ± 0.19
Push-off velocity ($m \cdot s^{-1}$)	2.02 ± 0.31[c]	2.02 ± 0.33[c]	2.01 ± 0.29[c]	2.17 ± 0.37[o,s,b]	2.06 ± 0.33
First gliding distance (m)	2.40 ± 0.57	2.60 ± 0.69	2.50 ± 0.67	2.43 ± 0.69	2.47 ± 0.65
First gliding time (s)	1.21 ± 0.42	1.34 ± 0.52	1.31 ± 0.44	1.29 ± 0.41	1.28 ± 0.45
First gliding depth (m)	0.48 ± 0.09[s,b]	0.72 ± 0.15[o,b,c]	0.53 ± 0.14[o,s]	0.49 ± 0.13[s]	0.55 ± 0.16
Transition distance (s)	1.08± 0.20	1.08 ± 0.24	1.09 ± 0.16	1.10 ± 0.21	1.09 ± 0.20
Transition time (s)	0.98 ± 0.22	0.92 ± 0.20	0.96 ± 0.18	0.96 ± 0.19	0.96 ± 0.20
Transition gliding depth (m)	0.62 ± 0.15[s]	0.86 ± 0.18[o,b,c]	0.67± 0.20[s]	0.65 ± 0.17[s]	0.70 ± 0.20
Second gliding distance (m)	0.80 ± 0.24	0.86 ± 0.30	0.88 ± 0.28	0.88 ± 0.30	0.85 ± 0.28
Second gliding time (s)	0.77 ± 0.26	0.83 ± 0.36	0.86 ± 0.32	0.85 ± 0.35	0.82 ± 0.32
Second gliding depth (m)	0.61 ± 0.17[s]	0.76 ± 0.18[o,b,c]	0.62 ± 0.19[s]	0.62 ± 0.17[s]	0.65 ± 0.19
Breakout distance (m)	5.94 ± 0.86	6.12 ± 1.00	6.04 ± 0.93	6.02 ± 0.99	6.04 ± 0.94
Breakout time (s)	4.83 ± 0.95	4.99 ± 1.03	4.83 ± 0.97	4.79 ± 0.99	4.86 ± 0.98
Time-out (s)	7.30 ± 0.92	7.09 ± 0.97	7.07 ± 0.84	7.13 ± 0.89	7.12 ± 0.89
NPO_X (N)	1.64 ± 0.19	1.66 ± 0.22	1.67± 0.17	1.59 ± 0.24	1.64 ± 0.20
NPO_Y (N)	19.41± 8.25[s,c]	15.31± 8.35[o]	21.12 ± 10.07[c]	13.23 ± 5.42[o,b]	17.23 ± 8.65
NPO_Z (N)	49.36 ± 24.99	45.81 ± 37.63	36.37 ± 20.59	62.84 ± 44.57	48.96 ± 34.14
NPO_ Impulse (Z) (Ns)	34.02 ± 25.07[s,b]	21.91± 15.46[o,c]	17.56 ± 8.64[o,c]	31.14 ± 49.38[s,b]	26.70 ± 21.33
DPO_X (N)	21.66 ± 11.03[s,b,c]	12.99 ± 5.36[o]	14.74 ± 8.63[o,c]	8.03 ± 3.24[o,b]	14.64 ± 11.14
DPO_Y (N)	64.92 ± 37.27[s]	37.28± 20.18[o,b,c]	70.08± 43.10[s]	56.07 ± 27.76[s]	56.86 ± 35.05
DPO_Z (N)	145.45 ± 76.20[b]	140.090± 65.50[b]	194.41± 119.14[o,s,c]	141.44 ± 30.50[b]	153.65 ± 78.90
DPO_ Impulse (Z) (Ns)	53.07 ± 30.50[b]	52.03± 33.61[b]	57.75 ± 39.48[o,s,c]	49.92± 33.11[b]	53.04 ± 33.87
D_1 (N)	-33.93 ± 7.56[c]	-36.40 ± 9.34[c]	-36.49 ± 5.39[c]	-40.57 ± 8.19[o,s,b]	-36.73 ± 8.32
D_2 (N)	-62.70 ± 25.57	-62.86 ± 25.56	-63.27± 25.83	-67.29 ± 26.82	-62.59 ± 25.35
C_{D1}	-0.74 ± 0.11	-0.72 ± 0.10	-0.75 ± 0.10	-0.76 ± 0.09	0.74 ± 0.10
C_{D2}	-1.16 ± 0.38	-1.16 ± 0.37	-1.10 ± 0.27	-1.20± 0.38	-1.14 ± 0.36
15 m turn time (s)	16.53 ± 1.53	16.41 ± 1.47	16.27 ± 1.60	16.67 ± 1.52	16.48 ± 1.52

o,s,b and c: significantly different from *open*, *somersault*, *bucket* and *crossover* turn ($p < 0.05$).

The best subsets regression for turn-in and turn-out to predict 15 m turning time in each backstroke to breaststroke turning technique are presented in **Table 4** and **Table 5**. Regarding the *open* turn, there were three predictors (7.5 m time-in, average SL and hand contact time) explained 86 % ($R^2 = 0.86$; $p < 0.01$) for turn-in, five predictors (first gliding distance, first gliding time, second gliding depth, turn -out time and DPO_Z) explained 93 % ($R^2 = 0.93$; $p < 0.01$) for turn -out on the 15 m turning time. For the *somersault* turn, there were three predictors (7.5 m time-in, 2.5 m time and rotation time) explained 78 % ($R^2 = 0.78$; $p < 0.01$) for turn-in, seven predictors (wall contact time, first gliding distance, breakout distance, breakout time, turn-out time, DPO_Y and C_{D2}) explained 92 % ($R^2 = 0.92$; $p < 0.01$) for turn -out on the 15 m turning time, respectively.

For the *bucket* turn, there were three predictors (7.5 m time-in, 2.5 m time-in and last upper limbs -wall distance) explained 89 % ($R^2 = 0.89$; $p < 0.01$) for turn-in, five predictors (foot plant index, push - off velocity, second gliding distance, turn-out time and C_{D1}) explained 92 % ($R^2 = 0.92$; $p < 0.01$) for turn -out on the 15 m turning time. For the *crossover* turn, there were four predictors (7.5 m time-in, 2.5 m time-in, average SL and rotation time) explained 87 % ($R^2 = 0.87$; $p < 0.01$) for turn-in, seven predictors (breakout time, turn-out time, NPO_Y, NPO_Z, D_1, D_2 and C_{D2}) explained 90 % ($R^2 = 0.90$; $p < 0.01$) for turn -out on the 15 m turning time, respectively.

Table 4. Data obtained from multiple regression analysis for turn-in variables.

Turns	Variables	B	*R*	*p*	Full model	
***Open* turn**	Constant	4.49		0.01**	*R*	0.93
	7.5 m time-in	1.61	0.81	0.001**	R^2	0.86
	Average SL	-1.00	-0.13	0.04*	*p*	0.001
	Hand contact time	-0.81	-0.11	0.04*		
	Equation : 15 m turn time = 4.49 + 1.61x 7.5 m time-in – 1.00 x Average SL – 0.81 Hand contact time					
	Variables	**B**	***R***	***p***	**Full model**	
***Somersault* turn**	Constant	2.26		0.04*	*R*	0.86
	7.5 m time-in	1.27	0.59	0.001**	R^2	0.78
	2.5 m time-in	1.86	0.36	0.01**	*p*	0.001
	Last upper limbs -wall distance	-0.69	-0.11	0.11		
	Rotation time	-0.99	-0.16	0.03*		
	Equation : 15 m turn time =2.26 + 1.27 x 7.5 m time-in + 1.86 x 2.5 m time-in) – 0.99 x Rotation time					
	Variables	**B**	***R***	***p***	**Full model**	
***Bucket* turn**	Constant	1.56		0.04*	*R*	0.95
	7.5 m time- in	1.45	0.73	0.001**	R^2	0.89
	2.5 m time- in	0.94	0.23	0.03*	*p*	0.001
	Last upper limbs -wall distance	-0.76	-0.13	0.02*		
	Equation: 15 m turn time = 1.561 + 1.45x 7.5 m time-in + 0.94 x 2.5 m time-in – 0.76 x Last upper limbs -wall distance					
	Variables	**B**	***R***	***p***	**Full model**	
***Crossover* turn**	Constant	5.05		0.01**	*R*	0.93
	7.5 m time- in	2.21	1.18	0.001**	R^2	0.87
	2.5 m time- in	-1.68	-0.36	0.03*	*p*	0.001
	Average SL	-1.23	-0.16	0.03*		
	Rotation time	-0.79	-0.14	0.02*		
	Equation: 15 m turn time =5.05 + 2.21x 7.5 m time-in – 1.68x 2.5 m time-in – 1.29 x average SL – 0.79 x rotation time					

* and ** significant for p < 0.05 and 0.01 (respectively).

Table 5. Data obtained from multiple regression analysis for turn-out variables.

Turns	Variables	B	R	p	Full model	
***Open* turn**	Constant	-0.85		0.01	*R*	0.94
	Tuck index	-0.52	0.51	0.31	R^2	0.93
	First gliding distance	1.01	0.34	0.01**	*p*	0.01
	First gliding time	-1.09	0.41	0.01**		
	Second gliding depth	-0.92	0.35	0.01**		
	7.5 m turn-out time	1.99	0.09	0.01**		
	NPO_X	0.52	0.29	0.08		
	NPO_Y	0.01	0.01	0.12		
	NPO_Impulse	-0.00	0.00	0.07		
	DPO_Z	0.01	0.00	0.01**		
	Equation: 15 m turn time = - 0.85 + 1.01x first gliding distance - 1.09 x first gliding time - 0.92 x second gliding depth + 1.99 x turn -out time + 0.01x DPO_Z					
	Variables	**B**	***R***	***p***	**Full model**	
***Somersault* turn**	Constant	8.44		0.001**	*R*	0.93
	Wall contact time	0.94	0.36	0.01**	R^2	0.92
	Push-off velocity	0.37	0.20	0.08	*p*	0.01
	First gliding distance	0.33	0.15	0.04*		
	Breakout distance	-1.02	0.29	0.01**		
	Breakout time	0.61	0.22	0.01**		
	Turn out time	1.03	0.14	0.01**		
	DPO_Y	-0.01	0.00	0.01**		
	DPO_Z	-0.01	0.01	0.10		
	C_{D2}	-0.72	0.17	0.10		
	Equation: 15 m turn time = 8.44 + 0.94 x wall contact time + 0.33 x first gliding distance - 1.02 x breakout distance + 0.61x breakout time + 1.03 x turn-out time - 0.01x DPO_Y - 0.72 x C_{D2}					
	Variables	**B**	***R***	***p***	**Full model**	
***Bucket* turn**	Constant	5.28		0.01**	*R*	0.94
	Foot plant index	-0.78	0.35	0.03*	R^2	0.92
	Push-off time	1.30	0.78	0.10	*p*	0.01
	Push-off velocity	-0.47	0.24	0.04*		
	Second gliding distance	-0.75	0.27	0.01**		
	Turn -out time	1.47	0.09	0.01**		
	DPO_X	0.01	0.01	0.07		
	C_{D1}	0.43	0.19	0.03*		
	Equation: 15 m turn time = 5.28 - 0.78 x foot plant index - 0.47 x push - off velocity - 0.75x second gliding distance + 1.47 x turn -out time + 0.43 x C_{D1}					
	Variables	**B**	***R***	***p***	**Full model**	
***Crossover* turn**	Constant	5.35		0.01**	*R*	0.92
	Tuck index	-1.06	0.64	0.11	R^2	0.90
	Push-off velocity	-0.46	0.25	0.07	*p*	0.01
	Breakout time	-0.18	0.09	0.04*		
	Turn-out time	1.74	0.11	0.01**		
	NPO_Y	-0.05	0.02	0.01**		
	NPO_Z	0.01	0.00	0.01**		
	D_1	-0.01	0.01	0.02*		
	D_2	-0.01	0.00	0.03*		
	C_{D2}	0.76	0.28	0.01**		
	Equation : 15 m turn time = 5.35 - 0.18 x breakout time + 1.74 x turn-out time - 0.05 x NPO_Y + 0.01 x NPO_Z- 0.01 x D_1 - 0.01 x D_2 + 0.76 x C_{D2}					

* and ** significant for p < 0.05 and 0.01 (respectively).

Discussion

The main aim of the current study was to identify the biomechanical features of backstroke to breaststroke transition techniques (*open*, *somersault*, *bucket* and *crossover*) in age-group swimmers. We believed that 15 m turning time performance is described by combining contributions from the turn-in and turn-out phases, as well as different combinations of feature variables depending on the chosen backstroke to breaststroke transition technique. As expected, general turn-in performance can be predicted mostly by faster times during the 7.5 m, 2.5 m to the wall. The average SL is a predictor of turn-in performance for both open and crossover turns, with faster rotation time being the most relevant variable for somersault and crossover turns. The last upper limbs-to-wall distance, which refers to kinesthetic awareness and sense of space, affects bucket turn performance. Our results from the turn-out phase highlighted the importance of the interaction between kinematic and kinetic variables at the wall contact and push-off phase, which influenced on turn-out performance across all backstroke to breaststroke turns studied. However, the importance of the turn-out variables changes depending on the chosen technique.

***Open* turn**

The 7.5 m time-in, average stroke length and hand contact time were the three key variables for the turn-in performance, while the first gliding distance, first gliding time, second gliding depth, turn-out time and dominant push-off_Z force were identified as key for the turn-out. Our results are consistent with some previous findings in elite swimmers that indicated that their turn-in performance was highly associated with their total turn time in the 200 and 400 m backstroke to breaststroke (Mason and Cossor, 2001). From the perspective of turn-in performance, the simple direction switch from the supine to the prone position during the *open* turn may require specific skills to maintain the swimming speed that incorporates the fastest rotation or pivot execution (Blanksby et al., 2004; Webster et al., 2011).

It has been reported that the optimization of the relationships between the kinematic, kinetic and hydrodynamic variables can directly influence turn-out performance (Termin and Pendergast, 1998; Vilas-Boas et al., 2010; Pereira et al., 2015). The *open* turn turn-out performance mainly depends on the interaction between the kinetic variable (dominant push-off_Z force) and the four kinematic–temporal variables (first gliding distance, first gliding time, second gliding depth and turn-out time). Theoretically, the peak perpendicular force, total impulse and wall contact time kinetic features are key factors of swimming turns (Prins and Patz, 2006), with the dominant peak push-off_Z force being the key kinetic variable in the present study. It tended to be slightly lower than data previous obtained in breaststroke (557 ± 109 N; Blanksby et al., 1998), rollover backstroke (229 ± 70 N; Blanksby et al., 2004) and tumble turns (693 ± 228 N; Blanksby et al., 1998) in age-group swimmers. However, this is not particularly surprising considering that the age-group swimmers from our study depicted a slower rotation with a tendency to spend a short preparatory push-off time (33%), which could lead to a lower maximum normalized peak force and impulse.

From the perspective of turn-out efficacy, the optimization of the underwater gliding depth, gliding time and gliding distance will directly affect turning performance (Termin and Pendergast, 1998; Chainok et al., 2021). The first gliding distance and time, second gliding depth and turn-out time were identified as key variables and appeared to be advantageous for performing *open* turn. In the current study, the first and second gliding distances, as well as the breakout distance and time, were slightly shorter in the *open turn* than in the other three turns.

***Somersault* turn**

The key mechanical features of the turn-in phase of the *somersault* turn mainly depended on the time-in (7.5 and 2.5 m) and rotation time. Given the high impact of the turn-in phase on the 15 m turning performance, the swimming approach (7.5 m and 2.5 m turn-in times) and rotation times should be more deeply considered. The *somersault* turn, comparing to the *open* turn findings, suggest that a faster approach could directly influence the turn time. Since the execution of the *somersault* turn requires a hand touch at the wall before rotating from the supine to the prone position, the rotation is critical. At this backstroke to breaststroke transition, the rotation time tended to be slightly slower than those previously studied in the rollover backstroke (Blanksby et al., 2004) and breaststroke turns (Blanksby et al., 1998) by age-group swimmers.

The analysis of the turn-out variables revealed that the wall contact time, first gliding distance, breakout distance, breakout time and turn-out time (kinematic–temporal), dominant push-off peak_Y force (kinetic and C_{D2} (hydrodynamic) variables were those affecting the 15 m turn time. Based on the pull-out strategy evidence, breakout distance, breakout time and turn-out time were identified as the important variables, indicating that age-group swimmers should select their own individual strategies by considering the breakout distance and the time to maximise the pull-out performance (Blanskby et al., 2004). The longer first gliding distance in *somersault* turn may be related to a lower dominant peak push-off_Y coupled with a deeper foot plant, suggesting that age-group swimmers should try to minimize the up or down movement of the all body during push-off, which could lead to a longer and deeper gliding (Blanskby et al., 2004).

Contrary to the expectations, the dominant peak push-off_Y force (about 26% of the mean peak_Z force) was selected as a critical predictor of the 15 m turn time. Theoretically, push-off force with the feet pushing up or down directly affects the push-off velocity and tends to be inversely related with rollover time (Blanksby et al., 2004; Pereira et al., 2015). The evidence from this study points to the notion that a suitable feet push-off position and wall contact time can directly affect the performance of the subsequent horizontal push-off force and impulse (Blanksby et al., 2004), as well as the push-off velocity (Pereira et al., 2015).

In the discussion of turn-out performance, it is essential to consider swimmers hydrodynamic characteristics and pull-out strategy (Chainok et al., 2021). In the *somersault* turn, push-off from the wall that is completely ventral and without any relevant rotation of the body may eventually lead to lower hydrodynamic drag (Pereira et al., 2015). The current study C_{D2} of the *somersault* turn was slightly high, probably due to the lower foot plant index during the push-off phase that might directly affect the gliding path adopted during the pull-out phase (see table 3). Even so, this value tended to be higher than those obtained in national-level breaststrokers (0.61–0.72; Vilas-Boas et al., 2010) and similar to data determined by computational fluid dynamics (0.85–1.06; Marinho et al., 2011).

***Bucket* turn**

Multiple linear regression analysis indicated that optimal turn-in performance mainly depends on the 7.5 and 2.5 m times-in and last upper limbs–wall distance. There was a direct relationship between 15 m turn time and 7.5 m time-in (r = 0.93) and 2.5 m time-in (r = 0.85), and a small inverse relationship between 15 m turn time and last upper limbs–wall distance (r = -0.13). As in the *open* and *somersault* turns, speed-in was an essential influencing factor of turning performance, in agreement with the previous literature on elite (Nicol et al., 2019) and Olympic swimmers (Mason and Cossor, 2001). The last upper limbs–wall distance was similar among the four turning techniques (range 0.45-0.57 m), evidencing a tendency for consistency in the approaching speed, resulting in an optimal last upper limbs wall distance and leading to faster turn-in.

The foot plant index, push-off velocity, second gliding distance and turn-out time (kinematic-temporal) and C_{D1} (hydrodynamic) variables were identified as the key variables for the backstroke to breaststroke turning performance. From the perspective of push-off efficacy, it is advantageous to address the appropriate lower extremity at wall contact with a greater tuck index and optimal feet planting (30–40 cm depth), which will facilitate the best horizontal push-off velocity (Clothier et al., 2000; Prins and Patz, 2006). However, the turning technique showed no main effect on push-off velocity and the linking and interaction of the kinematic variables at the wall contact and push-off phase can be considered a partial contribution of the biomechanical variables to turning performance. In the current study, the tuck index and, concomitant with a longer wall contact time tended to be higher than those for the butterfly turn (0.56 ± 0.11 s and 0.37 ± 0.09 s; Ling et al., 2004) and for the breaststroke turn (0.58 ± 0.13 s and 0.39 ± 0.08 s; Blanksby et al., 1998), performed by age-group swimmers. The foot plant index (0.55 ± 0.18) was also higher than the one previously obtained in flip turn performed by university swimmers (0.45 ± 0.10; Prins and Patz, 2006).

As determined before using inverse dynamics, the first gliding position at the breaststroke underwater path was more hydrodynamic than the second one, allowing lower S, C_D and D values for the same range of speeds (Vilas-Boas et al., 2010). The C_{D1} calculated in the *bucket* turn tended to be higher than that calculated in national-level breaststrokers (0.46 ± 0.08; Vilas-Boas et al., 2010), probably due to the lower gliding velocity and anthropometric characteristics of our age-group swimmers. Our data and the available literature also suggest that age-group swimmers need to be concerned about minimizing hydrodynamic drag by controlling their gliding position (body shape and length) along with their optimal gliding depth (range 0.4–0.6 m) (Lyttle et al., 2000; Vilas-Boas et al., 2010; Chainok et al., 2021).

***Crossover* turn**

We have observed that the optimal *crossover* turn-in performance can be identified by the 7.5 and 2.5 m times-in, average stroke length and rotation time, with the first two variables displaying strong direct relationships with 15 m turn time and the mean stroke length relating inversely with the 15 m turn time. Notably, the turn-in time and the wall approach stroke length were the key variables in all the backstroke to breaststroke turning techniques, indicating that the wall approach strategy was consistent among them.

Theoretically, from the turn-in efficacy improvement perspective, it is important to maximize the approach speed and minimize the rotation time. In the current study, the turning technique had no main effect on rotation time, what came out as a surprise because, from a theoretical and technical perspective, differences in body rotation actions – which are characteristic of the different studied techniques, may directly affect rotation speed and turning performance. Interestingly, the implemented training program significantly improved rotation in all the backstroke to breaststroke turning techniques, inclusively with higher values than those previously presented for the rollover backstroke (0.70 ± 0.10 s; Blanksby et al., 2004), pivot breaststroke (1.15 ± 0.22 s; Blanksby et al., 1998), pivot butterfly (1.11 ± 0.18 s; Ling et al., 2004) and tumble freestyle turns (2.01 $m \cdot s^{-1}$; Blanksby, Gathercole and Marshal, 1996) performed by age-group swimmers.

Multiple linear regression analysis indicated that the breakout and turn out times, non-dominant peak push-off_Y and Z forces, and D_1, D_2 and C_{D2} are turn-out performance determinants and, due to the high impact of maximized breakout distance and streamlined position on the turn-out performance, the importance of those hydrodynamic variables should be emphasized. In fact, minimizing the hydrodynamic drag should be the primary consideration for improving backstroke to breaststroke turn-out performance. Typically, the first gliding position is more hydrodynamic than the second one, allowing lower S, D and C_D values for the same range of speeds (Vilas-Boas et al., 2010; Marinho et al., 2011; Chainok et al., 2021). The *Crossover* turn had g higher D_1, D_2 and C_{D2} values than the other studied turns, which may be justified by: (i) a worst streamline performance due to the lateral body movements that occurs from the wall push-off to the first gliding position may (Lyttle et al., 1998; Termin and Pendergast, 1998) and (ii) the lower gliding velocity and control of the body shape and length while gliding. The current study *Crossover* D_1, D_2 and C_{D2} values were also slightly higher than previous values obtained in national-level swimmers (Vilas-Boas et al., 2010).

Our push-off force results are consistent with Araujo et al. (2010) findings indicating the highest normalized horizontal peak force contributes the most to enhancing turning performance in freestyle flip turns performed by national and international level swimmers, while increasing the upward or downward wall push-off was found to have a negative impact on turn-out performance during rollover backstroke turn in age-group swimmers (Blanskby et al., 2004). Interestingly, the non-dominant Y and Z push-off forces plays a critical role determining symmetry of lower limbs push-off and subsequent gliding orientation. This finding implies that the *crossover*, in which the swimmer lateral push-off against the wall, may need a powerful extension of one of the lower limbs – possibly the dominant limb – to generate a symmetric push-off force.

Conclusion

The determinant variables of the different backstroke to breaststroke transition techniques change during both the turn-in and -out phases. Some kinematic–temporal variables are more relevant during turn-in, some kinetic variables gain relevance during turn-out (highlighting the importance of the push-off phase) and the hydrodynamic variables are important for all the studied transition techniques. Finally, the rotation and push-off phases were the stronger determinants of turning performance among all studied backstroke to breaststroke turns. Considering the key biomechanical variables that influence each turning performance in the current data, the development of a specific training program aiming to enhance turning skills, particularly focusing on the rotation and push-off phases, should be reconsidered by coaches who work with age-group swimmers, even if it implies in a longer training intervention.

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CHAPTER 3.

Backstroke to breaststroke turns muscular activity. A study conducted in age group swimmers.

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Abstract

The aims of this study were to compare surface electromyographic (EMG) activity and kinematic variables among open, somersault, bucket and crossover backstroke to breaststroke turning techniques, and identify relationships between the integrated electromyography (iEMG) and kinematics profile focusing on the rotation and push-off efficacy. Following a four-week of systematically increasing contextual interference intervention program, eight 12.38 ± 0.55 years old male swimmers randomly performed twelve repetitions (three in each technique) turns in and out of the wall at maximum speed until the 7.5 m reference mark. Surface EMG values of the right vastus lateralis, biceps femoris, tibialis anterior, gastrocnemius medialis, rectus abdominis, external oblique, erector spinae and latissimus dorsi were recorded and processed using the integrated electromyography (iEMG) and the total integrated electromyography (TiEMG) that was expressed as a percentage of iEMGmax to normalize per unit of time for each rotation and push-off phase. Complementarily, 2D sagittal views from an underwater video camera were digitized to determine rotation and push-off efficacy. The crossover turn presented the highest rotation and push-off iEMG values. Erector spinae and gastrocnemius medialis had the highest activity in the rotation and push-off phases (89±10 and 98±69%, respectively). TiEMG depicted a very high activity of lower limb muscles during push-off activity (222±17 to 247±16%). However, there were no relation between TiEMG and rotation and push-off time, tuck index and final push-off velocity during the rotation and the push-off phases across all the studied turning techniques. The rotation efficacy in age-group swimmers were dependent on rotation time ($p=0.04$). The different turning techniques were not distinguishable regarding iEMG activity as a possible determinant of rotation and push-off efficacy. Our study has direct implications for selecting appropriate exercises and designing training programs for optimizing the rotation and push-off phases of backstroke to breaststroke turning at young ages.

Key words: Surface electromyography, turning techniques, individual medley, young swimmer

Introduction

In competitive swimming the turning phase plays a critical role in determining the winners and the losers (Chow et al., 1984; Vilas-Boas et al., 2002; Prins and Patz, 2006) and should be a key factor of the training process (Blanksby et al., 1998; Faelli et al., 2021). Previously to the specialization training phase, when developing swimming fundamentals, coaches should include specific turns in their programs to enhance age-group swimmers effectiveness. Since there are different turning techniques, more than using subjective criteria, it is important to dispose of a deeper understanding of their particular demands, particularly regarding the execution and efficiency from the approach to the push-off phase.

The backstroke to breaststroke turn is, possibly, the most complex turning movement used in medley events (Maglischo, 2003; Gonjo and Olstad, 2020; Chainok et al., 2021) and its analysis is very difficult to carry out without appropriate technology (Vilas-Boas and Fernandes, 2002; Pereira et al., 2015; Chainok et al., 2016). In this specific turn, swimmers must touch the wall in a dorsal position and change the direction of motion using the open, somersault, bucket and crossover turning techniques (FINA swimming rules, SW 9.4 and 10.4; 2017-2021). Each one has different rotation mechanics and imposes different muscle recruitment and activation patterns, with the open turn being taught first due to its simplicity (Maglischo, 2003; Purdy et al., 2013; Gonjo and Olstad, 2020). Literature focusing on the biomechanical comparison of backstroke to breaststroke turning techniques is very scarce, probably due to the difficulties in analysing the integrated movement in different planes and axes, and the corresponding muscle activity (Blanksby et al., 1998; Veiga, Cala, Frutos, and Navarro, 2014; Pereira et al., 2015).

The interest in muscle activity assessment during swimming is not new (Lewillie, 1971; Clarys, 1983), with surface electromyography (EMG) contributing decisively to the understanding of the technical actions when propelling through the water (Clarys and Rouard, 2011; Figueiredo et al., 2013; Martens et al, 2015). EMG analysis was also implemented for characterizing the starting phase (de Jesus et al., 2011) and for training optimization (Clarys and Cabri, 1993; Martens et al., 2016), but few studies analysed the muscular actions during the turning phase (Pereira et al., 2015). In fact, the analysis of the EMG activity of backstroke to breaststroke turning techniques was not yet done, not being known if technical variations (e.g. different body positions during the rotation and wall push off) could directly influence performance.

Although the muscle activity assessment during the turning phase is interesting, an observation of mastery technical capability should be taken into consideration since it could directly to robustness and reliability of the EMG results. Consistent with the aforementioned perspectives, facilitate learning to mastery the four backstroke to breaststroke turning techniques in age-group swimmers may be obtained from the level of the swimmers, past experience and scheduling of practice sessions (Seifert et al., 2016; Silva et al., 2019; Chainok et al., 2021). A practice schedule offering systematic increases in contextual interference which the blocked, serial and random trials scheduling have been very promising for established learning sports skills (Porter and Magill, 2010; Broadbent et al., 2015; Buszard et al., 2017) and beneficial for the key properties of continuous and complex skills (Porter and Magill, 2010; Porter and Beckerman, 2016).

Since there is no comprehensive understanding of the relative importance of the biomechanical determinants of different backstroke to breaststroke turning techniques, it was aimed to compare the EMG activity levels of four backstroke to breaststroke turns. In addition, it was proposed to observe the eventual relationships between the integrated electromyography (iEMG) and rotation and push-off time, tuck index and final push-off velocity. We hypothesized, that (1) the EMG response of lower limb and core muscles during the rotation and push-off phases would be sensitive to the different backstroke to breaststroke turning techniques,(2) the correlations and contributions of total iEMG activity and selected kinematics are expected to be evident in the rotation and push-off efficacy. Since these data are very important for age-group swimmers in particular in which young swimmers must build and consolidate a specific and detailed motor patterm of the turn (Faelli et al., 2021), we have centred our attention on evaluating 11 and 12-years-old swimmers engaged in systematic increases in contextual interference training.

Materials and methods

Subjects

Eight young male swimmers (12.38 ± 0.55 years old, 1.55 ± 0.14 m of height, 44.6 ± 10.9 kg of body mass, 14.1 ± 5.3% of body fat, 18.8 ± 2.3 kg/m^2 of body mass index and 3.3 ± 0.7 of Tanner maturational status) volunteered to participate in the current study. Swimmers belong to the same swimming club, had 3.5 ± 1.4 years of competitive swimming experience and 178.3 ± 10.1 s of the best performance in the 200 m short-course individual medley (corresponding to 62.3 ± 6.8 % of the world junior record). The local ethics committee approved the experimental procedures and the swimmers parents provided written informed consent.

Training protocol

Swimmers had a 2 h theoretical-practical lesson to perfect each turning technique, with video and verbal descriptive/prescriptive feedbacks being given to correct eventual technical errors (Pereira et al., 2015). Afterwards, a systematically increasing contextual interference intervention program took place (40 min per session four times a week during one month). The difficulty level progressively increased, with appropriate challenges based on skill level (Jefferys, 2006), facilitating learning and improving performance (Guadagnoli and Lee, 2004). Swimmers followed a block schedule on the first fourth sessions (each one focusing on the open, somersault, bucket and crossover turns). Then, a serial schedule was implemented from the fifth to the eighth and from the ninth to the twelfth sessions (respectively 10 and 5 min per turning technique, with the later one repeating twice). A random schedule was followed in the last four sessions, with an equal number of trials per turning technique.

Testing procedures

Following the intervention period, and after a usual warm-up, swimmers randomly performed 12 maximal 25 m repetitions (c.f. Chainok et al., 2022; Gonjo and Olstad, 2021; 12.5 m swimming to the wall, turning, gliding and resuming swimming until the 12.5 mark). Each backstroke to breaststroke turning technique was repeated three times (with a 3 min interval in-between) and the corresponding average was taken for posterior analysis. An experienced researcher observed each repetition and, if not completed properly, the swimmer was asked to repeat after resting.

Data collection

EMG activity was recorded from the body right side by using bipolar EMG with an eight-channel device (Figueiredo et al., 2013; de Jesus et al., 2016). It were selected the muscles that play a dominant role on lower limbs action (Pereira et al., 2015), trunk motion and core stabilizing action (Marras et al., 1998; Kumar, 2010): vastus lateralis, biceps femoris long head, tibialis anterior, gastrocnemius medialis, rectus abdominis, external oblique, erector spinae and latissimus dorsi. Swimmers skin was shaved and cleaned to reduce skin impedance (Figueiredo et al., 2013; Martens et al., 2016). Active silver chloride surface electrodes (Dormo, Telic, S.A., Spain) with preamplifiers (AD621BNZ; Analog Devices, Norwood, MA, USA) were placed in accordance with the European Recommendations for Surface Electromyography (Hermens et al., 2000) and were waterproofed using an adhesive bandage (Rouard and Clarys, 1995; Lauer et al., 2013; Pereira et al., 2015).

Each swimmer performed three dry land maximal voluntary isometric contractions for each muscle studied, which were held 5 s (followed by 5 min rest) and verbal encouragement was given to the subjects. The maximal value of three measurements was defined for normalization (cf. Pereira et al., 2015; de Jesus et al., 2016). Swimmers wore a complete Fast Skin swimsuit (Speedo, Nottingham, UK) and the EMG cables come out from the lateral malleolus (with the ground electrode being positioned over the patella). The total gain of the amplifier was set at 1100, with a common mode rejection ratio of 110 dB, with the EMG signals being stored at a 1000 Hz sampling frequency on an acquisition card with a 16-bit analog-to-digital converter (BIOPAC Systems, Goleta, CA, USA).

Kinematic variables were recorded using an underwater digital video camera (HDR CX160E; Sony Electronics Inc., Japan) placed inside a waterproof housing (Sony SPK-HCH; Sony Electronics Inc., Japan) and operating at a 50 Hz sampling frequency and 1/250 digital shutter speed. It was fixed on a specially designed support at 5 m from the turning wall and 6.50 m from the swimmers sagittal plane, with the optical axis aligned perpendicularly to the sagittal plane (Araujo et al., 2010). To calibrate the performance space, a 4 m long, 1.5 m high and 2 m wide (horizontal, vertical and lateral axes) quadrangular frame was used (de Jesus et al., 2015). The swimming biomechanical model comprised four rigid linked segments identified as lower limbs, head, arms and trunk). The video images and the EMG signal were synchronized through a visible-light trigger (Pereira et al., 2015; de Jesus et al., 2016).

Data treatment

MATLAB 2008a software (Math Works, Natick, MA, USA) was used for EMG signal processing, with raw EMG signals filtered using a fourth-order Butterworth band-pass filter (bandwidth 20–450 Hz), rectified and averaged to obtain the full-wave signals. The rectified EMG integration was calculated per unit of time (iEMG/T) for each turning phase to eliminate the phase duration effect and EMG signals were partitioned in 40 ms windows to find the maximal iEMG values ($iEMG_{max}$) for all studied muscles. iEMG/T was expressed as a percentage of $iEMG_{max}$ to normalize the results (Clarys, 2000) and calculated per phase (Lauer et al, 2013; Martens et al., 2015). Moreover, to obtain a more comprehensive understanding of the EMG activity and kinematic variables relative contributions in determining rotation and push-off efficacy, it was summed the normalized muscle activity of the core muscles ($TiEMG_{CBRO}$ and $TiEMG_{CBPO}$) and of the lower limbs ($TiEMG_{LLRO}$ and $TiEMG_{LLPO}$) during those phases (Feger et al., 2014; Figueiredo et al., 2013).

Kinematic analyses comprised two intermediate phases of the backstroke to breaststroke turn (Pereira et al., 2015): (i) rotation, starting immediately before the hand entry during the last upper limbs cycle before turning and ending before the feet touch the wall and (ii) push-off, starting on the initial feet-wall contact and ending before the feet push-off the wall. The anatomical landmarks were manually digitized frame by frame using the Ariel Performance Analysis System (Ariel Dynamics, San Diego, USA), with the image coordinates transformed to 2D object-space coordinates using the Direct Linear Transformation algorithm (Abdel-Aziz et al., 2015). After a 6 Hz low-pass Butterworth image filtering, it were analysed the rotation and push-off durations, the tuck index (the ratio between the distance of the femur greater trochanter from the wall at foot contact and the actual trochanteric height; Prins and Patz, 2006) and the final push-off velocity (the hips displacement at the last frame when leaving the wall; Prins and Patz, 2006).

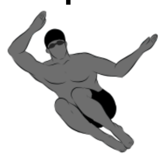
Statistical analysis

Statistics were performed in SPSS for Windows version 24 (SPSS, Chicago, IL, USA), with the significance level being set at 0.05. Since an iEMG data normal distribution could not be assumed due to the sample size (checked using the Shapiro–Wilk W test), the non-parametric Kruskal–Wallis H test was used to compare the differences of iEMG and selected kinematic variables among four backstroke to breaststroke turning techniques. In addition, the Mann–Whitney U test was used for pairwise comparisons and the Spearman correlation analysis was conducted to verify the existence of relationships between rotation and push-off iEMG and kinematic variables. Intraclass correlation coefficient (≥ 0.75, 0.40-0.75 and < 0.40 expressing good, moderate and poor reproducibility, respectively; van Asseldonk et al., 2014) was determined by comparing the core and lower limbs muscles iEMG and relative activation time in each turning phase.

Results

Fair to good iEMG and relative activation time reproducibility values were achieved between trials per turning phase for open, somersault, bucket and crossover turning techniques (ICC = 0.43-0.97, 0.59-0.97, 0.44-0.95 and 0.42-0.97, respectively). Data regarding the EMG activity during the rotation phase are shown in Table 1, with differences among the turning techniques being observed for all muscles (except for rectus abdominis) and with the erector spinae revealing greater activity than the other muscles ($\chi^2(7)=350.546$, $p < 0.001$). Figure 1 displays the median iEMG values during the rotation phase for the four turning techniques, with differences displayed for all muscles (except for the vastus lateralis).

Table1. The integrated electromyography (iEMG) mean ± SD, median and interquartile range (IQR) of the rectus abdominis (RA), external oblique (EO), latissimus dorsi (LD), erector spinae (ES), biceps femoris (BF), vastus lateralis (VL), tibialis anterior (TA) and gastrocnemius medialis (GM) in the rotation phase for each studied backstroke to breaststroke turning technique and respective of χ^2 and p-values of the comparisons among techniques**.**

iEMG (%)	**Turning techniques**												χ^2	*p*
	Open			**Somersault**			**Bucket**			**Crossover**				
														
	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR		
RA	43.37±23.37	49.60	31.15	32.12±15.01	25.20	19.93	48.51±19.75	50.30	18.35	41.19±15.08	41.00	14.25	6.41	0.09
EO	11.62±6.26	11.60	11.63	11.26±11.57	9.60	24.30	2.69±2.67	2.55	2.85	31.25±11.17	31.00	10.25	36.74	0.001
LD	7.91±5.22	7.90	8.45	8.41±5.26	8.40	3.15	7.89±4.41	7.90	1.68	50.88±22.42	51.00	37.75	37.33	0.001
ES	52.50±19.39	52.50	0.00	48.18±30.83	48.20	23.00	77.70±11.91	77.70	0.00	89.10±10.00	89.00	0.00	30.04	0.001
BF	48.47±18.67	48.50	29.48	33.11±22.53	29.15	29.80	43.96±17.76	44.00	10.73	42.00±18.68	41.00	14.75	7.312	0.001
VL	36.29±14.94	36.30	12.78	41.98±20.20	42.00	33.25	37.37±26.20	37.40	27.38	41.94±11.86	42.00	0.00	4.174	0.001
TA	9.59±6.21	8.45	3.58	23.89±14.50	23.90	12.45	12.91±4.63	12.90	2.03	36.19±12.35	36.00	0.00	35.30	0.001
GM	8.29±3.05	8.30	0.00	31.63±15.11	38.80	24.30	29.22±8.62	29.20	5.18	45.88±15.99	46.00	5.00	40.44	0.001

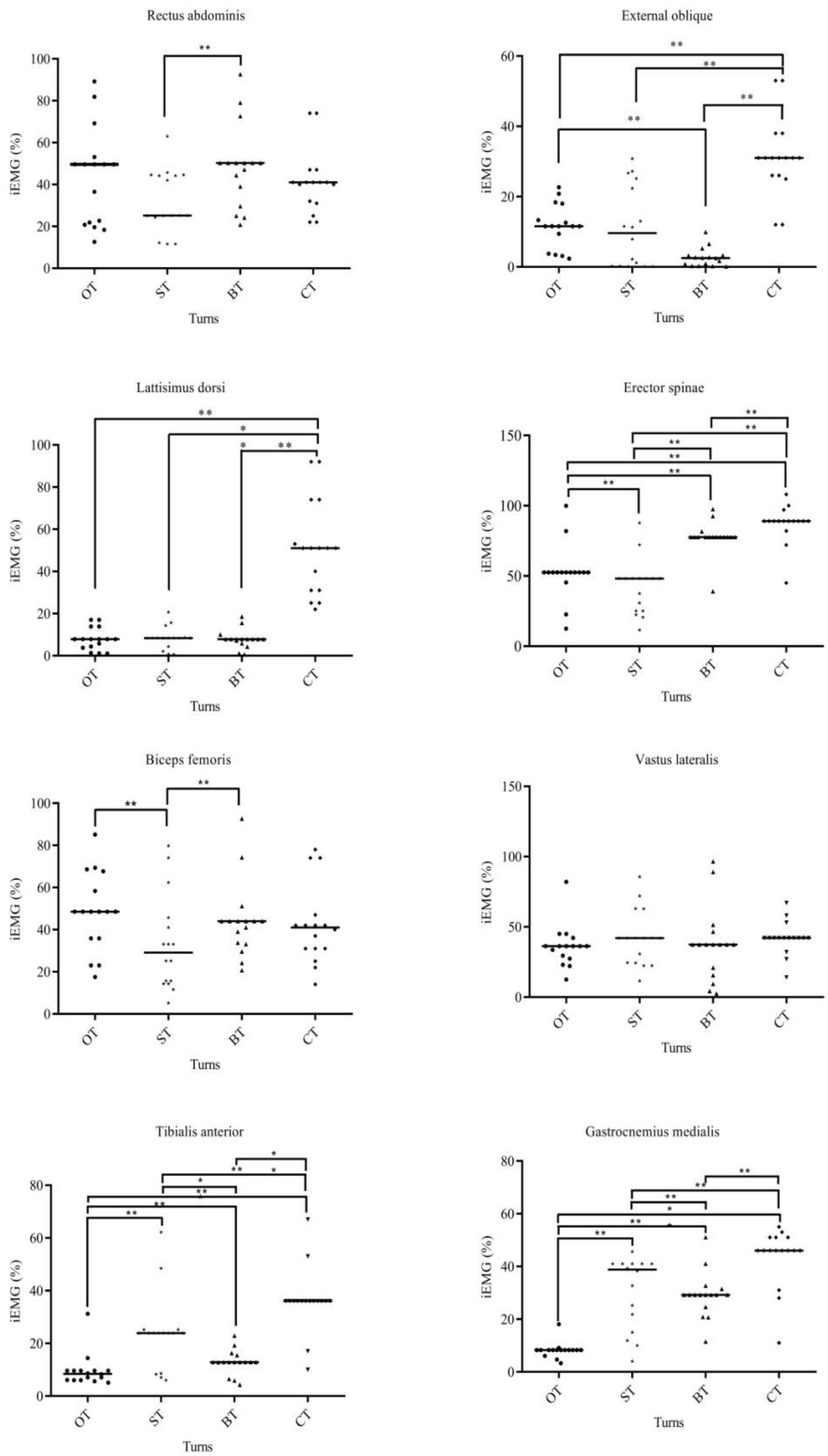


Figure 1. Median values of the normalized integrated EMG (iEMG; %) per phase of each muscle during the rotation phase of the open (OT), somersault (ST), bucket (BT) and cross-over (CT) backstroke to breaststroke turns.

Regarding the push-off phase, differences in the EMG activity were found in-between the studied turns when comparing the external oblique, latissimus dorsi, erector spinae, biceps femoris and vastus lateralis (Table 2), with the gastrocnemius medialis exhibiting higher activity than the other muscles ($\chi^2(7)=266.437$, $p < 0.001$). Figure 2 shows the median iEMG values during the push-off phase for the four turning techniques, evidencing differences between all muscles (except for the tibialis anterior and gastrocnemius medialis).

Regarding the total muscle activation and selected kinematics during the rotation phase, we have observed differences among the four turning techniques in $TiEMG_{CBRO}$, $TiEMG_{LLRO}$ and $TiEMG_{CBPO}$ and rotation time (Table 3). The crossover turn displayed the highest $TiEMG_{CBRO}$, $TiEMG_{LLRO}$ and $TiEMG_{CBPO}$ values among the evaluated turns, and the somersault turn presented the highest $TiEMG_{LLPO}$ value. Complementarily, $TiEMG_{CBRO}$, $TiEMG_{LLRO}$ and $TiEMG_{CBPO}$ were higher in the crossover technique than in the other turns ($p < 0.001$), while $TiEMG_{LLRO}$ was higher in the somersault than in the open turn ($p < 0.001$). The studied turning techniques differed regarding the average rotation times, with the fastest being the open and bucket comparing to the crossover and somersault techniques, but no differences were observed regarding the push-off time, tuck index and final push-off velocity. The tuck index was higher in the open than in the somersault turn, while the final push-off velocity did not differ among four turning techniques (Table 4).

Total muscle activation was not related to selected kinematic variables during the rotation and the push-off phases across all the studied turning techniques (Table 5). When analysing the contribution of iEMG activity and kinematics to rotation and push-off efficacy, it was only observed an inverse relationship between $TiEMG_{CBPO}$ and final push-off velocity in the somersault turn with all the other results not being statistically relevant.

Table 2. The integrated electromyography (iEMG) mean ± SD, median and interquartile range (IQR) of the rectus abdominis (RA), external oblique (EO), latissimus dorsi (LD), erector spinae (ES), biceps femoris (BF), vastus lateralis (VL), tibialis anterior (TA) and gastrocnemius medialis (GM) in the push-off phase for each studied backstroke to breaststroke turning technique and respective of χ^2 and p-values of the comparisons among techniques.

iEMG (%)	**Turning techniques**												χ^2	*p*
	Open 			**Somersault** 			**Bucket** 			**Crossover** 				
	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR		
RA	22.39±15.25	22.40	20.45	22.42±19.31	22.20	32.83	19.83±18.65	16.90	22.05	28.81±12.96	28.80	6.98	4.72	0.19
EO	3.30±4.36	0.80	5.43	2.89±4.60	0.45	2.70	2.93±4.80	0.60	2.63	4.32±1.99	4.30	2.10	9.19	0.03
LD	18.49±15.35	15.25	4.08	1.57±1.03	1.60	0.63	3.39±1.42	3.40	0.35	32.42±11.87	32.40	0.83	43.28	0.001
ES	42.78±15.35	42.80	1.95	32.41±16.08	32.40	13.05	54.88±21.73	54.90	13.12	63.89±16.14	63.90	10.50	24.55	0.001
BF	29.81±15.85	29.80	11.4	48.81±16.08	48.80	34.65	43.51±25.47	43.50	32.60	35.80±19.41	35.80	9.83	9.27	0.03
VL	60.72±12.98	60.70	9.60	60.40±34.88	60.40	66.13	48.49±45.55	32.30	37.47	39.28±22.80	39.30	25.90	11.16	0.001
TA	62.61±30.70	62.60	21.75	66.09±27.75	66.10	42.95	67.18±46.42	67.20	99.70	55.23±29.59	55.20	41.15	1.94	0.59
GM	77.12±38.96	77.70	67.61	71.78±27.75	92.70	80.73	77.76±45.74	76.05	92.50	91.38±48.40	98.25	69.55	1.88	0.61

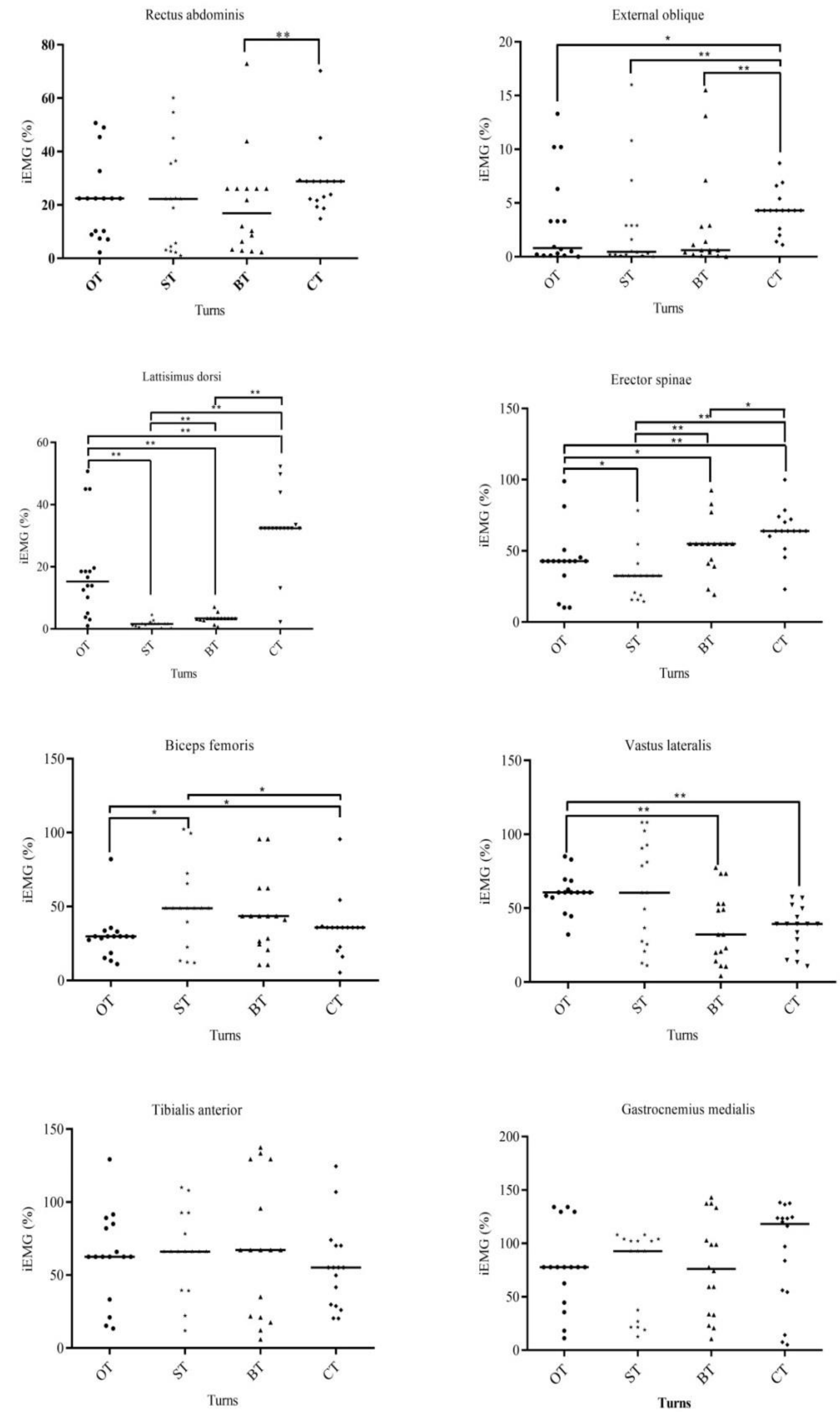


Figure 2. Median values for the normalized integrated EMG (iEMG; %) per phase of each muscle during the push-off phase of the open (OT), somersault (ST), bucket (BT) and cross-over (CT) backstroke to breaststroke turns.

Table 3. The total integrated electromyography (TiEMG) mean ± SD, median and interquartile range (IQR) and selected kinematic for each studied backstroke to breaststroke turning technique and respective of χ^2 and *p*-values of the comparisons among techniques.

iEMG (%)	Turning techniques												χ2	*p*
	Open			Somersault			Bucket			Crossover				
	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR		
$TiEMG_{CBRO}$ (%)	115.40±6.97	116.50	39.85	106.22±12.70	100.25	62.08	136.79±5.17	136.95	32.38	212.31±6.97	210.00	48.50	32.95	0.001
$TiEMG_{LLRO}$ (%)	102.64±6.81	98.70	35.03	130.61±6.58	139.20	44.50	123.46±9.03	123.50	30.25	166.00±8.59	166.00	45.00	22.18	0.001
$TiEMG_{CBPO}$ (%)	86.97±9.29	86.05	46.53	59.04±6.24	60.95	39.83	81.03±7.83	80.75	33.43	129.44±7.18	125.80	13.38	27.72	0.001
$TiEMG_{LLPO}$ (%)	230.85±10.85	224.40	71.60	247.09±16.13	239.25	101.35	236.93±16.69	231.45	105.02	221.67±16.69	220.75	41.05	1.54	0.67
Rotation time (s)	1.31±0.05	1.32	0.35	1.56±0.07	1.58	0.37	1.36±0.07	1.29	0.39	1.44±0.07	1.48	0.41	8.57	0.04
Push-off time (s)	0.29±0.018	0.27	0.14	0.32±0.02	0.32	0.11	0.28±0.01	0.28	0.01	0.32±0.17	0.27	0.14	2.98	0.39
Tuck index	0.64±0.032	0.64	0.21	0.54±0.03	0.54	0.10	0.58±0.03	0.58	0.12	0.56±0.02	0.56	0.06	4.73	0.19
Final push-off velocity ($m.s^{-1}$)	1.68±0.035	1.65	0.22	1.66±0.05	1.65	0.28	1.64±0.06	1.59	0.29	1.74±0.05	1.75	0.34	2.79	0.43

$TiEMG_{CBRO}$: total iEMG of core body muscles during rotation; $TiEMG_{LLRO}$: total iEMG of lower limbs during rotation; $TiEMG_{CBPO}$: total iEMG of core body muscles during push-off; $TiEMG_{LLPO}$: total iEMG of lower limbs during push-off.

Table 4. The post-hoc comparisons of the total integrated electromyography (TiEMG) and selected kinematic variables among four different backstroke to breaststroke turns**.**

Variables	Kruskal-Wallis H test		Mann-Whitney U test											
			Open vs. somersault		Open vs. bucket		Open vs. crossover		Somersault vs. bucket		Somersault vs. crossover		Bucket vs. crossover	
	H	Sig.	Z	Sig.	Z	Sig.	Z	Sig.	Z	Sig.	Z	Sig.	Z	Sig.
$TiEMG_{CBRO}$ (%)	32.95	0.001	98.00	0.26	72.00	0.04	10.00	0.001	61.00	0.01	15.50	0.001	15.00	0.001
$TiEMG_{LLRO}$ (%)	22.18	0.001	53.00	0.001	70.00	0.03	19.00	0.001	120.0	0.76	57.00	0.001	55.50	0.001
$TiEMG_{CBPO}$ (%)	27.72	0.001	66.00	0.02	109.50	0.49	40.00	0.001	74.00	0.04	11.00	0.001	25.00	0.001
$TiEMG_{LLPO}$ (%)	1.54	0.67	110.00	0.49	124.00	0.88	114.00	0.59	119.00	0.73	96.00	0.23	105.50	0.40
Rotation time (s)	8.57	0.04	59.00	0.001	126.0	0.94	88.00	0.13	69.00	0.03	98.00	0.26	94.00	0.20
Push-off time (s)	2.98	0.39	98.50	0.26	126.50	0.96	96.00	0.22	97.50	0.25	122.50	0.84	93.00	0.18
Tuck index	4.73	0.19	74.00	0.001	96.00	0.23	82.50	0.09	114.00	0.60	112.00	0.55	115.50	0.64
Final push-off velocity ($m.s^{-1}$)	2.79	0.43	122.00	0.82	103.50	0.36	105.00	0.39	116.50	0.67	98.50	0.27	86.50	0.12

$TiEMG_{CBRO}$: total iEMG of core body muscles during rotation; $TiEMG_{LLRO}$: total iEMG of lower limbs during rotation; $TiEMG_{CBPO}$: total iEMG of core body muscles during push-off; $TiEMG_{LLPO}$: total iEMG of lower limbs during push-off.
* and ** significant at $p < 0.05$ and 0.001 (respectively).

Table 5. Correlation coefficients between the total integrated electromyography (TiEMG) and selected kinematics variables in the rotation and push-off phase of each studied backstroke to breaststroke turning technique**.**

Turns	Statistical analysis values	Rotation phase			Push-off phase				
		Rotation time (s)	TiEMG $_{CBRO}$ (%)	TiEMG $_{LLRO}$ (%)	Final push-off velocity (m/s)	TiEMG $_{CBPO}$ (%)	TiEMG $_{LLPO}$ (%)	Push-off time (s)	Tuck index
Open	Spearman rho		-0.11	0.20		0.08	-0.23	0.01	0.32
	p-value		0.60	0.46		0.78	0.40	0.98	0.22
Somersault	Spearman rho		-0.18	-0.27		-0.50	0.20	0.33	-0.32
	p-value		0.51	0.31		0.04*	0.66	0.22	0.23
Bucket	Spearman rho		0.33	-0.01		-0.30	0.16	-0.03	0.15
	p-value		0.21	0.99		0.26	0.56	0.92	0.59
Crossover	Spearman rho		-0.19	-0.20		0.18	-0.19	-0.01	-0.14
	p-value		0.47	0.45		0.50	0.49	0.98	0.60

$TiEMG_{CBRO}$: total iEMG of core body muscles during rotation; $TiEMG_{LLRO}$: total iEMG of lower limbs during rotation; $TiEMG_{CBPO}$: total iEMG of core body muscles during push-off; $TiEMG_{LLPO}$: total iEMG of lower limbs during push-off.
* and ** significant at $p < 0.05$ and 0.001 (respectively).

Discussion

The current study is the first that measured and compared muscular activity among open, somersault, bucket and crossover backstroke to breaststroke turning techniques and was pioneer in assessing the relationships between EMG activity and selected kinematic variables regarding the rotation and push-off actions efficacy. Overall, the crossover turn presented the highest rotation and push-off iEMG values and erector spinae and gastrocnemius medialis had the highest activity in the rotation and push-off phases.TiEMG depicted a very high activity of lower limb muscles during push-off activity and there were no relation between TiEMG and selected kinematic variables during the rotation and the push-off phases across all turning techniques. In addition, the rotation efficacy in age-group swimmers were dependent on rotation time.

The orientation of the backstroke to breaststroke turns during the rotation phase may be described by the variations in the longitudinal rotation (Chainok et al., 2021), which relates to muscular activation and affects the rotation efficacy. The rotation phase execution is initiated by plantar flexion of the ankle, followed by knee and hip flexion, allowing the knees to be brought up to the chest, reducing the moment of inertia about the axis of rotation (Webster et al., 2011). Most of the selected lower and upper limb muscles were highly recruited in the crossover turn, which involves complex whole-body movements by combining twisting and rotational asymmetrical movements on both horizontal anterior-posterior and medial-lateral axes.

In the current study, the upper limb muscles (external oblique, lattisimus dorsi and erector spinae) were mainly activated during combined asymmetrical twisting and rotational movements, probably because torso dynamics is influenced by co-contraction recruitment, increasing trunk stiffness and resulting in greater muscle activity (Lee et al., 2006). Therefore, our hypothesis was partly supported. Notably, biceps femoris and rectus abdominis were the most active muscles in the open turn, acting as prime movers of the tucked position to facilitate knee flexion and assist hip flexion in the succeeding phases of rotation (respectively). The greater biceps femoris and rectus abdominis activation observed during the rotation phase could be related to the synergistic activation of the muscles crossing the knee and hip to provide a mechanical advantage in trunk to lower limbs coordination within posture and rotation movement (Mathiyakom et al., 2006; Yeadon and Hiley, 2014).

It was observed a high activation of vastus lateralis during somersault and crossover rotation, probably because it is the prime responsible for hip flexion. Vastus lateralis mainly contributes to the net joint moment and work done at the joints crossed while doing a reverse somersault (Mathiyakom et al., 2006). Interestingly, the gastrocnemius medialis was highly recruited when swimmers strongly swung backward to switch direction, meaning that age-group swimmers attempted to avoid excess drag and increased angular momentum by performing knee flexion and ankle plantar flexion while ultimate twist of the asymmetric hip movement. In this way, the net joint moment acting at the distal joint (ankle) is expected to be relatively large and, then, a relatively small action at the proximal joint (hip) is required to control the observed motion (Mathiyakom et al., 2006).

Integrated EMG interpretation becomes more complex when movements of large amplitude are involved, particularly regarding the core body muscles. As the swimmer initiates rolling in the bucket, open and somersault turns, lower limbs are brought up to the chest in a tight tuck, by co-activation of the hips and abdominal muscles (Chainok et al., 2016; Kieran, Rylands and Canham, 2020). The erector spinae and rectus abdominis were the main muscles activated during the rotation phase and the initiation of the hip flexion in a rotated posture is achieved by the activities of the contralateral external oblique and ipsilateral latissimus dorsi, followed by the erector spinae (Kumar et al., 1996; Kumar et al., 2002a).

In fact, the erector spinae is one of the strongest muscles (most often recruited in bending movements) and is capable of producing more of a twisting moment when the torso is flexed (Marras et al., 1998). Its activity is highest at 40° of knee flexion due to greater mechanical disadvantage and having not reached the state of flexion–relaxation (Kumar, 2010). In contrast, the latissimus dorsi and external oblique muscles reduce their activity when the twisting motion is performed in an asymmetric posture (Marras et al., 1998), as it occurs in swimming turns. In the crossover turn, the erector spinae and latissimus dorsi were mainly activated during combined asymmetrical twisting and rotational movements, probably because torso dynamics is influenced by co-contraction recruitment, increasing trunk stiffness and resulting in greater muscle activity (Lee et al., 2006).

As expected, the main gastrocnemius medialis and tibialis anterior activities were observed during the push-off probably due to their role during the explosive lower limbs extension (Pereira et al., 2015). This high activation can be explained by the muscular co-contraction contribution (Lyttle et al., 1999) and the kinetic link of the monoarticular and biarticular muscles contributing from the proximal (hip) to distal (ankle) joints (Putnam, 1993; Jacobs et al., 1996). In fact, close kinetic chain movement involves multi-joint action developing mainly in biarticular muscle groups (Prokopy et al., 2008), with the closed kinetic chain of the lower limb extensors being directly related with jumping performance (Blackburn and Morrissey, 1998).

The stretch shortening cycle during the push-off consists on an eccentric contraction, mainly in biarticular muscles (quadriceps and gastrocnemius), while contact is followed by a concentric contraction producing an explosive movement while pushing off (Komi, 2000; Prins and Patz, 2006; Sousa et al., 2007). Therefore, it seems that a suitable contact time spent in the active phase and maximizing the use of elastic energy involved in the stretch shortening cycle for young swimmers can be used effectively during the push-off phase (Faelli et al., 2021).

Rotation and push-off efficacy have been accomplished using key kinematic, kinetic and hydrodynamic variables (e.g.Veiga et al., 2014). Nonetheless, comprehensive analysis of neuromuscular activation and selected kinematic factors including rotation time, push-off time, tuck index and final push-off velocity would provide a better understanding of those variables on backstroke to breaststroke turns. The slowest rotation time was found in the somersault turn that was lower than previously found for backstroke and breaststroke turns performed by age-group swimmers (Blanksby et al., 1998; Blanksby et al., 2004). It is also known that the rotation time varies widely among turning techniques regarding the degree of longitudinal rotation and different global body movement (Maglischo, 2003; Prins and Patz, 2006) and that task difficulty and learner past experiences could have a meaningful influence on the ability to learn dynamic movements (Guadagnoli and Lee, 2004).

No differences were found when comparing push-off time and final push-off velocity among the four studied backstroke to breaststroke turns. The influence of biomechanical variables linked to the contact phase on the final push-off velocity has been one of the most critical determinants of the flip and rollover backstroke turns (Blanksby et al., 2004; Prins and Patz, 2006; Pereira et al., 2015). The push-off time of the four different backstroke to breaststroke turns was relatively higher compared to data previously published regarding the flip turn (Lyttle et al., 1999). The wall contact time spent in the "active" push-off phase was likely to result in faster push-off velocities due to the mechanical and neuromuscular benefits of stretch shortening cycle (Prins and Patz, 2006; Faelli et al., 2021).

The final push-off velocities of the analysed turns were lower than those previously reported for age-group swimmers (Blanksby et al., 1996; Blanksby et al., 1998; Blanksby et al., 2004). It is possible that our young swimmers had not yet proper developed rotating and mechanical strategies to optimize the tuck index or the percentage of wall contact time spent in the active phase to maximize push-off efficacy. The tuck index in the open turn was higher than in the other turns, being known that higher tuck indexes lead to greater peak propulsive forces and lower wall contact times (Blanksby et al., 2004) However, the current study found that most tuck index values were closer to those previously reported for the breaststroke and the backstroke turns performed by age-group swimmers (Blanksby et al., 1998; Blanksby et al., 2004).

Following the previous studies that used the total EMG muscle activation as an analytical marker of task intensity and total muscle activation pattern for each extremity (Feger et al., 2014; Donnelly et al., 2015), our study provides a framework encouraging the use of EMG analysis for swimming training purposes. $TiEMG_{CBRO}$, $TiEMG_{LLRO}$ and $TiEMG_{CBPO}$ differed among turns due to the execution diversity and multi-link mechanism during rotation (in both lower limbs and core-body muscles). In addition,

$TiEMG_{CBRO}$ and $TiEMG_{LLRO}$ exhibited the highest activation in the crossover turn. As expected, different turning technique rotation mechanics and strategies might directly reflected the increase of core body muscles co-activation to speed up the rotation time. During the push-off phase, $TiEMG_{LLPO}$ showed a very strong activity (with similar patterns among the four turning techniques), with gastrocnemius medialis being the main muscle activated during that phase in both age-group (Blanksby et al., 2004) and national level swimmers (Pereira et al., 2015). However, children maximal neuromuscular activation is generally lower than that of adults due to dimensionality, intramuscular synchronization and agonist–antagonist co-activation (Dotan et al., 2012).

Contrary to our expectations, selected kinematic variables and total muscle activation of iEMG did not presented strong relationships with rotation and push-off efficacy. However, a preliminary observation revealed an inverse relationship between $TiEMG_{CBPO}$ and final push-off velocity in the somersault turn, indicating that push-off performance should mainly activate co-contraction of muscles of the lower extremities. Interestingly, $TiEMG_{CBPO}$ showed greater activation in the crossover turn than in the other turns. The current results underline that muscular activation of the core body and lower extremities clearly exhibits the higher muscle activation in the crossover turn throughout the rotation and push-off phases. Data indicate that multiple factors (like differences in perceptual and cognitive skills, inherent variations and task difficulty) might account for these findings.

The current study allows concluding that: (i) the highest iEMG muscle activation occurred in the crossover turn throughout the rotation and push-off phases; (ii) the erector spinae revealed the highest activity during the rotation phase; (iii) biarticular gastrocnemius medialis and monoarticular tibialis anterior were mainly activated during the push-off phase; (iv) $TiEMG_{LLPO}$ showed very high activity with similar patterns in all turns during the push-off phase; and (v) selected kinematic variables and total iEMG muscle activation of iEMG did not influenced the rotation and push-off efficacy. These data provide valuable mechanistic insights into rotation and push-off phases of the most used backstroke to breaststroke turns, deepening the current understanding of the mechanical function and need for co-activation of the musculoskeletal system of age group swimmers. Moreover, the knowledge obtained from biomechanical analyses of the backstroke to breaststroke turn has direct implications for selecting appropriate exercises and designing training programs for optimizing this specific rotation and push-off phases at young ages. Future studies on this issue should reveal even more details of value for designing strength and conditioning training programs specialized in closed kinetic chain of the lower limb for “active” push-off phase, strengthening core muscles to improve the effectiveness of muscles co-activation to speed up the rotation.

CHAPTER 4.

Backstroke to breaststroke turning performance in age-group swimmers: Hydrodynamic characteristics and pull-out strategy

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Abstract

We compared the hydrodynamic characteristics and pull-out strategies of four backstroke to breaststroke turning techniques in young swimmers. Eighteen 11 and 12-year-old swimmers participated in a four - week intervention program including 16 contextual interference sessions. The hydrodynamic variables were assessed through inverse dynamics, and the pull-out strategy kinematics were assessed with tracking markers followed by 12 land cameras and 11 underwater cameras. Swimmers randomly completed sixteen 30 m maximal backstroke-to breaststroke-open, somersault, bucket and crossover turns (four in each technique) with a three min rest. The data showed higher drag force, cross-sectional area and drag coefficient values for the first (compared with the second) gliding position. The crossover turn revealed the highest push-off velocity (2.17 ± 0.05 $m.s^{-1}$), and the somersault turn demonstrated the lowest foot plant index (0.68 ± 0.03; 68%), which could have affected the first gliding, transition and second gliding depths (0.73 ± 0.13, 0.86 ± 0.17 and 0.76 ± 0.17 m). The data revealed the consistency of the time spent (4.86 ± 0.98 s) and breakout distance (6.04 ± 0.94 m) among the four turning techniques, and no differences were observed between them regarding time and average velocity up to 7.5 m. The hydrodynamic characteristics and pull-out strategy of the backstroke to breaststroke turns performed by the age group swimmers were independent of the selected technique.

Key words: swimming; hydrodynamics; drag; strategy; age group

Introduction

Turning performance is determined by the efficiency of changing direction while swimming between the turn-in and turn-out phases. Consequently, swimmers should approach the wall by maintaining speed without compromising the ability to turn and push off the wall as powerfully as possible (allowing the highest wall-out velocity with the least possible drag) (Blanksby et al.,2004; Webster et al., 2011; Pereira et al., 2015). The swimming-related literature emphasizes that the total turning performance results from increased turn-out efficacy throughout the push-off, glide and swimming resumption phases (Lyttle et al., 2000; Prins and Patz, 2006; Naemi, Easson and Sanders, 2010). In fact, the optimized performance should derive from a balance between promising hydrodynamic propulsion and minimizing hydrodynamic drag (Lyttle et al., 2000; Silveira et al., 2019).

Theoretically, swimmers can improve their turn-out performance by improving their underwater gliding efficiency, both minimizing drag and optimizing underwater timing and distance (Naemi, Easson and Sanders, 2010). When gliding, passive drag (Dp) is mainly determined by the swimmer's body shape, velocity and depth (Chatard et al., 1990; Lyttle et al., 1999; Novais et al., 2012). The difference in the drag coefficient (C_D) can be attributed to varying body dimensions or to changes in body position (Clarys, 1979; Havriluk, 2005). Dp can be experimentally assessed by towing a swimmer in a fixed position (Clary, 1973; Lyttle et al., 2000) or through inverse dynamics (Vilas-Boas et al., 2010) and numerically using computer fluid analysis (CFD) (Zamparo et al., 2009; Novais et al., 2012; Costa et al., 2015).

The Dp during the breaststroke underwater action was investigated using inverse dynamics, and it was observed that the drag force (D), drag coefficient (C_D) and cross-sectional area (S) of the first gliding position were lower than those of the second gliding path (Vilas-Boas et al., 2010; Costa et al., 2015). However, none of these questions have been addressed in the backstroke to breaststroke turning action out of the wall. In this specific turn, swimmers adopt a pull-out strategy that is divided into four phases: first gliding, a transition phase (where an underwater upper and lower limb action takes place), second gliding and transition to the surface (Maglischo, 2003; Zamparo et al., 2009; Vilas-Boas et al., 2010)

Gliding performance depends on the initial velocity, as well as the deceleration magnitude and its duration (Naemi, Easson and Sanders, 2010). Furthermore, optimizing gliding distance and time by maximizing the velocity has also been suggested (Alcock, 2014). For instance, if the underwater lower limb action is initiated too early, resistance increases, slowing the swimmer prematurely. Conversely, by gliding for too long before the underwater lower limb action, a swimmer will decelerate to less than the race pace, wasting energy returning to free swimming speed (Lyttle et al., 2000; Costa et al., 2015). However, optimal timing of the pull-out strategy depends on each individual, since it is related to the time taken to reach the aimed competitive swimming velocity. Since no studies are available that focus on analysing backstroke to breaststroke turning performance in young swimmers, considering an integrated multifactorial approach, we aimed to compare the hydrodynamic characteristics and pull-out strategies regarding the turn-out performance of four backstroke to breaststroke turn techniques in certain age groups of swimmers.

Materials and Methods

Experimental Approach

The key mechanical features of the four studied backstroke to breaststroke turn techniques, considering the hydrodynamics and pull-out strategy, were obtained after intervention training sessions. Those key mechanical features were described and compared using selected kinematic and hydrodynamic factors. Four backstroke to breaststroke turns were identified, based on FINA rules SW 6.5 and 9.4 and the complex movement variations that specify body configuration and orientation in the rotation and push-off phases (Figure 1). A four-week intervention program of 16 systematically increasing contextual interference sessions (40 min each) was conducted in a 25 m (1.90 m deep) indoor pool. Subjects were assigned to train under this program and the practice difficulty progressively increased, with appropriate challenges beyond their skill levels (Jeffreys, 2006), to facilitate learning and improve performance

(Guadagnoli and Lee, 2004). Coaches were asked to allow swimmers to avoid intense efforts and substantial changes in training, dietary and sleep regimes during the experience period, particularly in the 48 h before each instance of data collection.

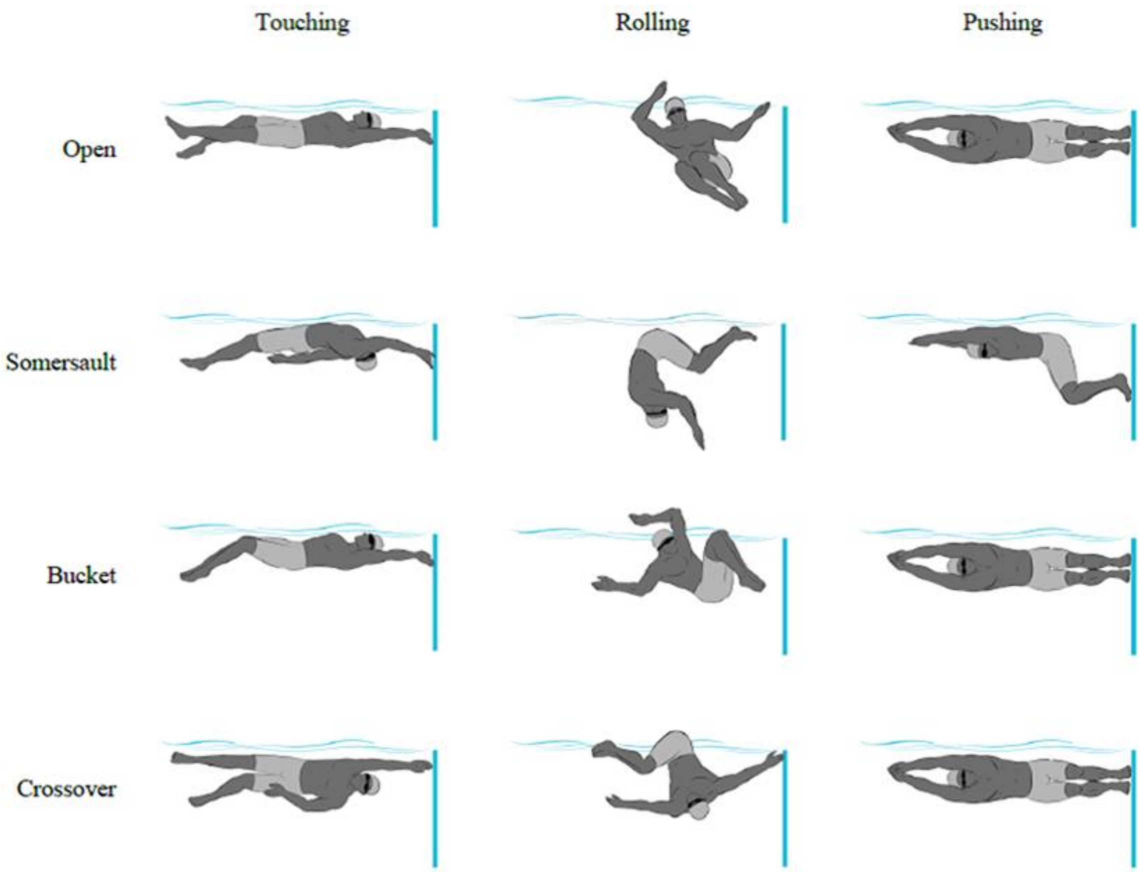


Figure 1. Representation of a swimmer's body orientations during the rotation and push-off phases for the four studied backstroke to breaststroke turning techniques.

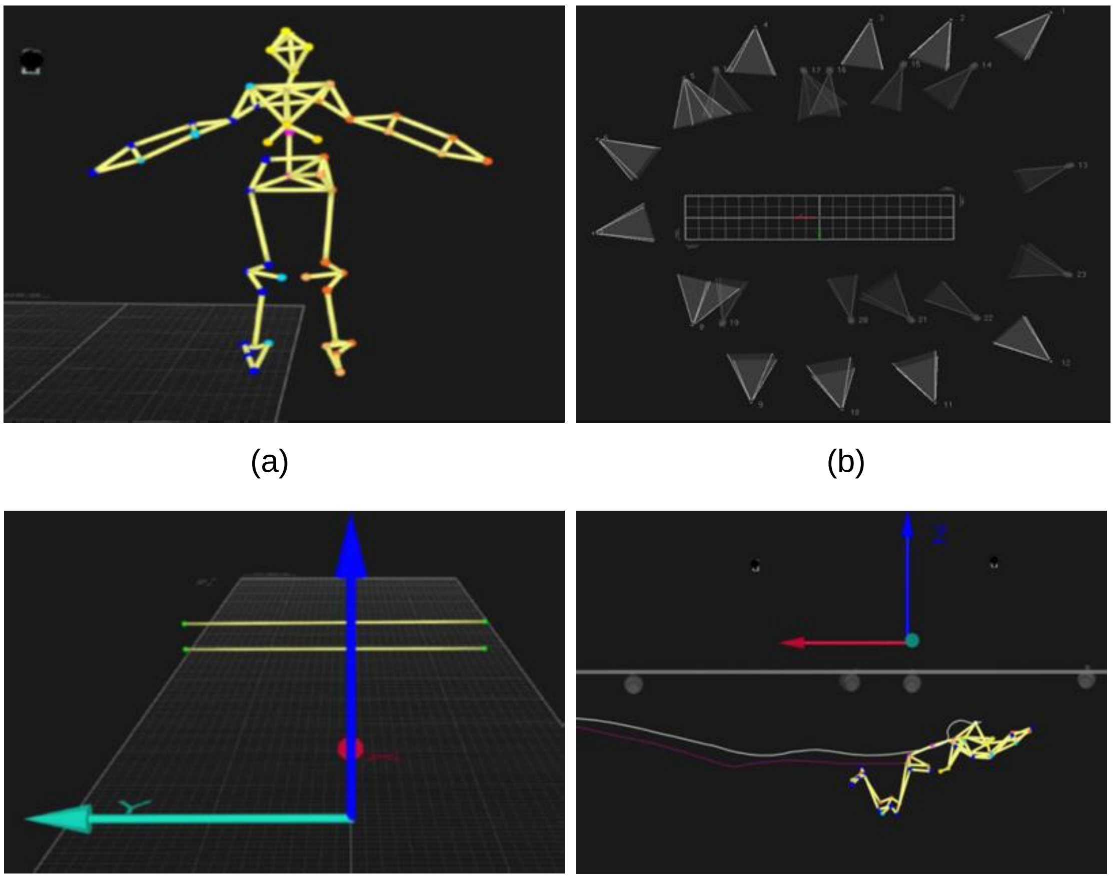
Swimmers followed a block-type schedule plan from the first to the fourth practice sessions (each focusing on a different turning technique), and a serial schedule was followed from the fifth to the eighth session (the A, B, C and D series were repeated for 10 min). A serial schedule was also followed from the ninth to the twelfth session (the 5 min series of A, B, C and D were repeated twice). Then, a random schedule was followed from the thirteenth to the sixteenth sessions, with an equal number of trials for each technique. Following the intervention period, swimmers randomly performed twelve repetitions, those being three repetitions of each turning technique (with 3 min of rest between trials). The trials started and finished from the middle of the pool, with swimmers performing turns in and out of the wall at maximum speed until the 15 m reference. An experienced researcher observed every turn and asked swimmers to repeat those not properly performed. The average values (from the three trials) obtained for each selected variable per turning technique were taken for posterior analysis.

Participants

Eighteen age group swimmers (ten males and eight females) participated in the study. Their main anthropometric, performance and training background characteristic means and standard deviations values were (for males and females, respectively) as follows: 12.45 ± 0.16 and 11.71 ± 0.18 years of age, 48.81 ± 3.57 and 43.47 ± 3.40 kg of body mass, 19.65 ± 0.77 and 18.97 ± 0.90 $kg.m^{-2}$ body mass index, 15.93 ± 1.81 and 18.06 ± 1.41% of fat mass, 158.50 ± 3.89 and 149.28 ± 2.71 cm in height, 157.82 ± 4.06 and 151.00 ± 2.67 cm arm span, 183.73 ± 5.60 and 192.38 ± 5.45 s 200 m individual medley short course best performance (representing 61.89 ± 8.69% and 67.56 ± 6.19% of the world junior record) and 3.56 ± 1.43 and 3.12 ± 1.13 years of competitive experience, and both were in Tanner stages 2–4. Swimmers, coaches and parents were informed of the investigation benefits and risks before signing an informed consent form to participate. The study was approved by the ethics board of the institution (code n° CEFADE 08.2014), and all procedures were in accordance with the Declaration of Helsinki.

Measurements

Subjects were photographed using scaled photographs (Clarys, 1979; Vilas-Boas et al., 2010) at a height of 3 m (measured from the ground reference plane) in the first and second gliding positions for S assessment using planimetry (Vilas-Boas et al., 2010). Kinematic data were recorded by automatically tracking 51 spherical retroreflective markers (see Figure 2 a panel) with a motion capture set-up that included 12 stationary overwater cameras and 11 underwater cameras (Oqus 3 and 4 series, Qualisys, Gothenburg, Sweden; see the panel in Figure 2 b) sampling at 100 Hz. Ten land-based system cameras were mounted along two opposite swimming pool lateral sides (covering the 15 m mark from the wall), and two others were positioned perpendicularly. Nine underwater cameras were also placed along the two opposite lateral sides of the pool just below the water surface (with the respective lenses focusing on the swimmer's trajectory), and the remaining two cameras were sitting at the bottom of the pool facing upward (Lauer, Rouard and Vilas-Boas, 2016). No camera was coplanar, and the wand calibration followed the three consecutive steps employed in processing and acquisition: underwater, above water and combined (merging the underwater and above-water views).



(a) (b)

(c) (d)

Figure 2. Kinematic data collection and data processing for (a) the full-body marker setup, (b) motion capture camera positioning, (c) referential system origin using four points of reflective markers and (d) sacrum and head kinematic traces during the pull-out phase.

Calibration was first performed with a static L-frame (positioned 7.5 m from the wall). Then, wand dynamic calibration was conducted using an L-shaped reference structure and moving a wand with two markers of 0.7495 m of interpoint distance (according to the manufacturer recommendations). Wand dynamic calibrations were performed separately underwater and overwater, and they were combined by merging a land-based and underwater system using dual media wand movements. A calibrated volume of ~30 m^3 and locations of 10 m (X, pointing horizontally and in the forward motion direction), 2.0 m (Y, horizontally and laterally toward the right of the swimmer) and 1.5 m (Z, vertically) were obtained. The origin of the referential system was set by using four points of reflective markers at the wall (corresponding to a position 7.5 m away from the wall) and the calibration mean precision value obtained was ~0.79 mm. Marker reconstruction accuracy reached 93.2%.

Data Processing

The hydrodynamic variables were assessed through inverse dynamics, considering D, C_D and S as previously proposed (Vilas-Boas et al., 2010; Costa et al., 2015). D was extracted from the relationship between the swimmer's body mass (m, with the added mass effect not being considered) and acceleration (a) for the first and second glides:

$$D = ma \quad (1)$$

The acceleration-to-time curve (a(t)) of the sacrum reflective marker was assessed during the first and second glides of the pull-out phase through numerical differentiation of the v(t) curve (filtered with a fourth-order Butterworth filter). The C_D for each gliding was calculated using the following transformation:

$$C_D=2D / \rho S v^2 \quad (2)$$

where D is the measured drag, ρ represents the water density (1000 $kg.m^{-3}$), S is the typical cross-section frontal area surface of the first and second gliding positions and v is the swimmer velocity relative to the flow (Vilas-Boas et al., 2010; Costa et al., 2015). S was directly measured through planimetry using the scaled photograph technique

(Clarys, 1979; Vilas-Boas et al., 2010; Costa et al., 2015) and was computed in MATLAB® 2014a (The Mathworks, Inc., Natick, MA, USA) as the summation of the triangles' areas (Vilas-Boas et al., 2010). The S digitizing reliability was evaluated from one randomly selected photograph of a swimmer digitized 10 times in each gliding position. The intraclass correlation coefficient (ICC) was 0.99. The mean values of the three independent digitizing trials were selected (panels in Figure 3 a–f).

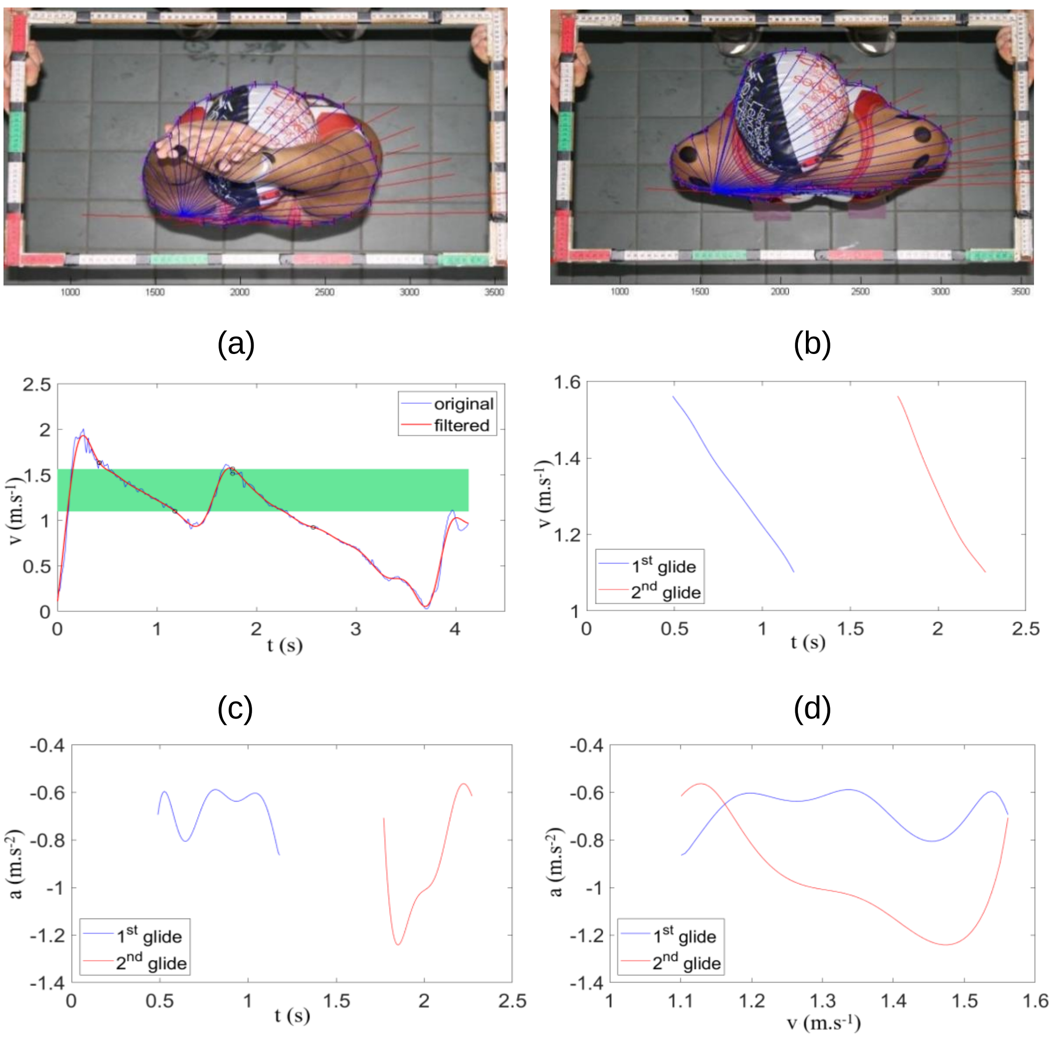


Figure 3. Hydrodynamic data collecting and processing. Body surface area was determined using the first (a) and second (b) gliding positions, and the v(t) data (c) was filtered with a 3 Hz cut-off low-pass fourth order Butterworth filter. The v(t) curve range of two successive gliding phases (d), the acceleration-to-time curve (a(t)) (e) and the acceleration-to-velocity curves ((a(v)) (f) are also displayed.

To determine the turn-out performance, it was necessary to examine the variation and relationships of the featured variables with factors possibly affecting the response to pull-out performance. Qualisys Track Manager (Qualisys, Gothenburg, Sweden) software was used to acquire the 3D kinematic data (see Figure 2d), which was then imported into the signal processing software (Acqknowledge v.3.9.0, BIOPAC Systems Inc., Santa Barbara, CA, USA). Each individual variable was digitally filtered with a 6 Hz cut-off digital filter (FIR, Window Blackman, 61 dB) to minimize artifact noise (Lauer, Rouard and Vilas-Boas, 2017). The kinematic variables selected to characterize the pull-out strategy are described in Table 1.

Table 1. Kinematic variables selected to analyze the pull-out strategies of backstroke to breaststroke turning techniques.

Variables	Definition
Push-off velocity ($m \cdot s^{-1}$)	Sacrum resultant velocity at the moment the feet left the wall.
Tuck index	Right hip distance from the wall at the beginning of push-off divided by the swimmer's lower limb length.
Foot plant index	Foot plant depth on the wall at the beginning of push-off divided by the swimmer's lower limb length.
First gliding distance (m)	Sacrum distance from the moment the feet left the wall to the transition phase's beginning.
First gliding time (s)	Sacrum time from the beginning of the feet leaving the wall to the transition phase's beginning.
First gliding depth (m)	Sacrum average depth during the first gliding.
Transition distance (s)	Sacrum distance from the initial hand separation or start of dolphin lower limb action until the upper limbs are extended at the body's sides.
Transition time (s)	Sacrum time from the initial hand separation or starting dolphin lower limb action until the upper limbs are extended at the body's sides.
Transition gliding depth (m)	Sacrum average depth during the transition phase.
Second gliding distance (m)	Sacrum distance from the first frame of the upper limbs being extended at body's sides to the instant the hands begin to move up from the body's sides.
Second gliding time (s)	Sacrum time from the first frame of the upper limbs being extended at the body's sides to the instant the hands begin to move up from the body's sides.
Second gliding depth (m)	Sacrum average depth during the second gliding.
Breakout distance (m)	Distance at which the head breaks the surface for the first time.
Breakout time(s)	Time at which the head breaks the surface for the first time.
Average pull-out velocity ($m \cdot s^{-1}$)	Average velocity from the moment the feet leave the wall to the head breaking the surface.
Time to 7.5 m (s)	Time from the feet leaving the wall to the head reaching the 7.5 m mark.

Statistical Analysis

After applying a Shapiro–Wilk normality test, mean and standard deviation computations for descriptive analysis were obtained for all variables. Sphericity was verified using the Bartlett test before using repeated ANOVA measures to detect any main effect of the hydrodynamics characteristics, pull-out strategy or the four backstroke to breaststroke turning techniques. Provided that a significant effect was found, Bonferroni post hoc analysis was conducted for each pairwise comparison. To provide an unbiased estimate of the population effect size, a partial omega squared (ω^2) measurement was adopted (Levine and Hullett, 2002) and classified as small (<0.06), moderate (0.07–0.14) or large (>0.14) (Cohen, 1988).

Results

The S of the second gliding was higher than the first gliding (584.67 ± 1.14 vs. 632.18 ± 0.08 cm^2, p = 0.028). The other hydrodynamic characteristics of the first and second gliding positions at the open, somersault, bucket and crossover backstroke to breaststroke turning techniques are displayed in Table 2. Even if the gliding velocities were similar in all turns, the second gliding displayed higher D and C_D values compared with the first one. The results demonstrate that there were no main effects of the turns on S, D and C_D among the four turning techniques.

The kinematics and pull-out variables among the four backstroke to breaststroke turning techniques are displayed in Table 3. Regarding the three examined components of the push-off phase, statistical analysis highlighted the main effect of the turns on the push-off velocity, with the highest value occurring in the crossover turn. There were no differences for the tuck index among the four turning techniques. The foot plant index decreased from the somersault turn to the open, bucket and crossover turns. For the first gliding phase, it was also observed that the depth was higher in the somersault turn than in the bucket, crossover and open turns. An effect of the turns on the transition phase between the two gliding phases (the underwater upper and lower limb actions) was observed only for the gliding depth. Post hoc analyses demonstrated that the transition depth was higher in the somersault turn than in the bucket, crossover and open turns.

Table 2. Mean ± SD of the hydrodynamic characteristics of the first and second gliding in the four studied backstroke to breaststroke turning techniques.

Variables	Turning Techniques					p	ω^2
	Open	Somersault	Bucket	Crossover	All		
V_1^{st} ($m.s^{-1}$)	1.31 ± 0.14	1.33 ± 0.13	1.32 ± 0.12	1.32 ± 0.15	1.32 ± 0.13	0.89	0.001
V_2^{nd} ($m.s^{-1}$)	1.31 ± 0.02	1.33 ± 0.02	1.32 ± 0.02	1.32 ± 0.02	1.32 ± 0.13	0.89	0.001
C_{D1}^{st}	−0.74 ± 0.16	−0.72 ± 0.27	−0.74 ± 0.30	−0.75 ± 0.14	−0.74 ± 0.22	0.90	0.001
C_{D2}^{nd}	−1.14 ± 0.44	−1.12 ± 0.34	−1.17 ± 0.47	−1.27 ± 0.51	−1.18 ± 0.45	0.17	0.01
D_1^{st} (N)	−36.73 ± 9.99	−39.01 ± 13.48	−40.28 ± 9.75	−41.78 ± 7.10	−39.35 ± 0.67	0.08	0.02
D_2^{nd} (N)	−61.65 ± 5.76	−64.13 ± 5.42	−62.25 ± 12.34	−69.73 ± 16.55	−64.44 ± 15.11	0.25	0.001

V_1^{st}: mean velocity of the first gliding curve; V_2^{nd}: mean velocity of the second gliding curve; C_{D1}^{st}: drag coefficient of the first gliding position; C_{D2}^{nd}: drag coefficient of the second gliding position; D_1^{st}: drag force of the first gliding position; D_2^{nd}: drag force of the second gliding position.

In the second gliding phase, the main effect of the turning techniques was only observed with the depth. Post hoc analyses demonstrated that the value for the second gliding depth was highest in the somersault turn. Values for the second gliding depth were highest for the somersault turn, followed by the bucket, crossover and open turns. The turning techniques did not elicit changes in the breakout distance, breakout time, velocity at breakout or average pull-out velocity. Notably, the time to 7.5 m was not influenced by different backstroke to breaststroke turning techniques and pull-out strategies.

Table 3. Mean ± SD values, *p* values and effect sizes regarding the kinematics and pull-out variables of four turning techniques of the backstroke to breaststroke turns.

Variables	Turning Techniques					*p*	ω^2
	Open	Somersault	Bucket	Crossover	All		
Push-off velocity ($m \cdot s^{-1}$)	2.03 ± 0.04 ^{c}	2.02 ± 0.05 ^{c}	2.01 ± 0.04 ^{c}	2.17 ± 0.05 ^{o,s,b}	2.06 ± 0.03	0.01	0.05
Tuck index	0.71 ± 0.14 ^{s}	0.76 ± 0.10 ^{o}	0.76 ± 0.09	0.72 ± 0.12	0.74 ± 0.12	0.09	0.00
Foot plant index	0.59 ± 0.02 ^{c}	0.68 ± 0.03 ^{b,c}	0.55 ± 0.03 ^{s}	0.50 ± 0.02 ^{o,s}	0.58 ± 0.19	0.01	0.11
First gliding distance (m)	2.41 ± 0.56	2.60 ± 0.64	2.48 ± 0.58	2.44 ± 0.63	2.47 ± 0.65	0.07	0.02
First gliding time (s)	1.21 ± 0.42	1.34 ± 0.49	1.32 ± 0.38	1.29 ± 0.3.78	1.28 ± 0.45	0.18	0.01
First gliding depth (m)	0.56 ± 0.13 ^{s}	0.73 ± 0.13 ^{o,b,c}	0.57 ± 0.13 ^{s}	0.57 ± 0.13 ^{s}	0.61 ± 0.15	0.01	0.25
Transition distance (s)	1.09 ± 0.20	1.08 ± 0.22	1.10 ± 0.14	1.09 ± 0.19	1.09 ± 0.02	0.75	0.00
Transition time (s)	0.99 ± 0.22	0.92 ± 0.19	0.97 ± 0.16	0.96 ± 0.18	0.96 ± 0.19	0.23	0.01
Transition gliding depth (m)	0.62 ± 0.14 ^{s}	0.86 ± 0.17 ^{o,b,c}	0.67 ± 017 ^{s}	0.65 ± 0.16 ^{s}	0.70 ± 0.20	0.01	0.29
Second gliding distance (m)	0.78 ± 0.27	0.82 ± 0.34	0.86 ± 0.27	0.85 ± 0.32	0.85 ± 0.28	0.44	0.00
Second gliding time (s)	0.78 ± 0.03	0.83 ± 0.05	0.86 ± 0.05	0.85 ± 0.05	0.83 ± 0.30	0.19	0.01
Second gliding depth (m)	0.62 ± 0.17 ^{s}	0.76 ± 0.17 ^{o,b,c}	0.62 ± 0.16 ^{s}	0.62 ± 0.15 ^{s}	0.65 ± 0.18	0.01	0.14
Breakout distance (m)	5.97 ± 0.87	6.13 ± 0.94	6.05 ± 0.80	6.02 ± 0.91	6.04 ± 0.94	0.85	0.00
Breakout time (s)	4.84 ± 0.94	5.01 ± 0.96	4.83 ± 0.84	4.78 ± 0.91	4.86 ± 0.98	0.42	0.00
Average pull-out velocity ($m \cdot s^{-1}$)	1.06 ± 0.13	1.08 ± 0.14	1.08 ± 0.14	1.07 ± 0.12	1.07 ± 0.13	0.74	0.00
Time to 7.5 m (m)	7.19 ± 0.89	7.09 ± 0.91	7.06 ± 0.72	7.12 ± 0.82	7.12 ± 0.90	0.75	0.00

^{o}, ^{s}, ^{b} and ^{c}: different from the open, somersault, bucket and crossover turns (respectively).

Discussion

The purpose of this study was to compare the hydrodynamic characteristics and the pull-out strategies during turn-out performance of certain age group swimmers when performing four backstroke to breaststroke turning techniques. Any differences in time and average velocity to 7.5 m, as well as in the pull-out strategy, after a four week intervention program among the open, somersault, bucket and crossover turns were not observed. Contrary to our expectations, the data did not allow for classifying any of the turning techniques as the most effective in terms of turn-out performance (considering hydrodynamic characteristics and pull-out strategy variables). However, there are possible explanations for the obtained results, allowing one to better understand the hydrodynamic characteristics and pull-out strategies used by young swimmers.

Our swimmers' S values in both the first and second gliding positions were relatively low when compared with the data from national level swimmers (740.42 ± 101.89 and 784.25 ± 99.62 cm^2) (Vilas-Boas et al., 2010). Regarding the hydrodynamic characteristics, (i.e., D, C_D and v), no differences were found among the four studied turns in the two gliding positions. Our findings confirmed the previous results, which suggested that D was associated with anthropometric differences with respect to age and body alignments (Vilas-Boas et al., 2010; Benjanuvatra, Blanksby and Elliott, 2001). In the literature, push-off propulsion optimization and pull-out strategy have clearly demonstrated their influence for improving turn performance, since kinematic factors (like tuck index, foot plant position and push-off velocity) play critical roles and directly affect pull-out performance (Prins and Patz, 2006). Theoretically, there are two determining factors that directly affect glide performance: the initial push-off velocity and hydrodynamic drag (which acts to decelerate the swimmer) (Lyttle et al., 1999). We observed higher values for the average push-off velocity when swimmers performed the crossover turn, with data presenting evident similarities with previous studies in age group swimmers that performed butterfly and breaststroke open turns and front crawl tumble turns (2.00 ± 0.20, 2.01 ± 0.21 and 2.01 $m \cdot s^{-1}$, respectively) (Blanksby, Gathercole and Marshall, 1996; Ling et al., 2004), but the average push-off velocity was higher when compared with the backstroke turn (1.70 ± 0.30 $m \cdot s^{-1}$) (Blanksby et al., 2004).

The higher push-off velocity values observed in the crossover turn could be due to the rotational skills of (Pereira et al., 2015) and lateral body positioning during push-off by the swimmer (considered as more hydrodynamic than the prone position) (Araujo et al., 2010). These findings should be related to the kinematic factors of the foot plant position that differed among the four turning techniques; the somersault turn tended to display a slightly higher foot plant index than any other turns and also compared with the data reported before (0.40 m and 0.45 m) (Lyttle et al., 1998; Prins and Patz, 2006). However, there was no difference in the tuck index among the four studied turning techniques. In the current study, the mean distance of the hip from the wall was ~74% (71–76%) of the length of the swimmer's lower limbs, which was slightly higher than the values reported before in the breaststroke and backstroke turns (58% and 60%), also for the age group swimmers (Blanksby et al., 1998; Blanksby et al., 2004).

As was already shown, the pull-out strategy optimization can substantially impact swimming turn performance, with a properly executed streamlined posture, gliding depth and optimal underwater lower and upper limb action timing and distance being key factors for turn-out performance (Havriluk, 2005; Naemi, Easson and Sanders, 2010). The current study provides additional evidence for the glide depth during pull-out importance. The first gliding, transition and second gliding depth values were slightly higher in the somersault than in any other backstroke to breaststroke turn, making it possible to assume that the foot plant position during push-off could be responsible for the glide depth path. Moreover, it was suggested before that swimmers should achieve a ~0.40–0.60 m glide depth to obtain maximum drag reduction benefits at fast exertions, suggesting that the values observed for the somersault turn might not be advantageous. Indeed, no differences in final turning performance were observed.

Choosing the correct gliding duration and distance, as well as proper lower limb action timing, for maximizing velocity should be an individual strategy. The current data showed that for all the studied turning techniques, swimmers spent ~ 1.21–1.34 s covering the 2.41–2.60 m first gliding distance before initiating the transition, corroborating the values proposed by Lyttle et al. (2000) (which also did not find any differences between lateral and ventral gliding positioning). An important piece of feedback is that swimmers should use an approximately ~0.4–1.0 m glide depth and wait ~1 s before initiating underwater lower limb action (Lyttle et al., 2000; Sanders and Byatt-Smith, 2001). In fact, if it is initiated too early, the resistance will increase, slowing down the swimmer prematurely (Lyttle et al., 2000). Moreover, concurrent with a higher S, D and C_D in the second gliding (than in the first position), there was a tendency for the swimmer's average velocity to decrease, in line with the findings of Termin and Pendergast (1998) that the average velocity did not increase due to the upper and lower limb actions during the transition phase.

Nonetheless, in spite of the current study's interesting findings, there are some limitations that should be considered and addressed in future research. A correctly done underwater phase generally incorporates pushing off the wall, good streamlining and initiating transition at the appropriate time, but we only focused on the kinematics of the first component (by analysing the final push-off velocity, tuck index and foot plant index). Consequently, an integrative analysis combining the kinematic and kinetic characteristics of pushing off the wall associated with the turn-out strategy hydrodynamic variables should be incorporated in future research. Our age group swimmers were pooled for evaluation (in consideration of a reasonable sample size) with gender differences not being considered. We feel that swimmers should be analyzed by sex in future research, particularly if samples with swimmers after puberty are used. Last but not least, a control group should be added in future studies, allowing for the minimization of random effects on dependent variables over time and obtaining stronger experimental research designs.

Conclusion

The hydrodynamic characteristics (such as S, D and C_D), as well as the pull-out strategy, were similar in the age group swimmers, irrespective of the backstroke to breaststroke turning technique used. Taken together with previous recommendations available in the literature, these findings highlight that optimizing propulsion during push-off, the glide depth, limb actions during transition (without decreasing velocity) and distance and time optimization could directly influence turn-out performance. We are confident that the current data is useful and will serve as a base for future studies centred on the relationship between biomechanical variables and how a change in hydrodynamic characteristics and pull-out strategy can provide a better understanding of the most efficient backstroke to breaststroke turns.

CHAPTER 5.

Modeling and predicting the backstroke to breaststroke turns performance in age-group swimmers

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Abstract

The purpose of the present study was to identify the performance determinant factors predicting 15 m backstroke to breaststroke turning performance using and comparing linear and tree-based machine learning models. The temporal, kinematic, kinetic and hydrodynamic variables were collected from 18 age-group swimmers (12.08 ± 0.17 yrs) using 23 Qualisys cameras, two tri-axial underwater force plates and inverse dynamics approach. The best models were obtained: (i) with Lasso linear model of the leave-one-out cross-validation in open turn (MSE = 0.011; R^2 = 0.825) and in the somersault turn (MSE = 0.011; R^2 = 0.734); (ii)the Ridge of the leave-one-out cross-validation (MSE = 0.016; R^2 = 0.763) for the bucket turn and (iii) the AdaBoost tree-based model of the leave-one-out cross-validation for the crossover turn (MSE = 0.016; R^2 = 0.644). Model's selected features revealed that optimum turning performance was very similarly determined for the different techniques, with balanced contributions between turn-in and turn-out variables. Results of both the linear and tree-based machine learning models approaches showed that the relevant features for each backstroke to breaststroke turning technique are specific, as well as the best modelling method, and may influence differently the development of specific training intervention programs.

Key words: age-group swimmers; supervised learning; non-linear modelling**;** backstroke to breaststroke

Introduction

Turning performance is generating considerable interest as a key factor in swimming race total performance (Nicol et al., 2019). Until now, improvements in turning performance have been focused on determining optimal technique (Blanksby et al., 2004; Prins and Patz, 2006), evaluating the effects of technical changes on performance (Araujo et al., 2010; Pereira et al., 2015), predicting mechanical determinant factors (Pereira et al., 2015) and pacing strategy contributing to turning performance (McGibbon et al., 2018; Saavedra et al., 2012; Zamparo et al., 2012). A single variable does not strongly enough predict swimming turns performance and a holistic approach, as suggested in butterfly and freestyle turns, should be considered also for backstroke to breaststroke turns (Nicol et al., 2019). Consequently, several methods focused on subjective opinion and scientific data for a number of variables have been suggested to understand the relationship and contribution of each biomechanical domain (temporal, kinematic, kinetic, electromyographic and hydrodynamic) on turning performance (Blanksby et al., 2004; Nicol et al., 2019; Pereira et al., 2015).

Scientists have also developed research designs and statistics comparing mean differences between turning techniques (Araujo et al., 2010; Nicol et al., 2019; Pereira et al., 2015), correlation and regression with performance (Blanksby et al., 2004; Ling et al., 2004) and its determinant biomechanical factors (Blanksby et al., 1998, 2004; Prins and Patz, 2006). However, these research designs and methodological approaches only presented the magnitude of correlations and a linear or simplistic model of determinant variables, while the interplay of various nonlinear biomechanic interactions could not be addressed in depth.

Much research has been conducted on the modelling and prediction of swimming performance using linear differential equations or regression analysis (Edelmann-Nusser et al., 2002), hierarchical multiple regression (M. J. Costa et al., 2013), path analysis (Morais et al., 2012), latent growth curve modelling (Morais et al., 2014) and structural equation modelling (Barbosa et al., 2010; Fischer and Kibele, 2016). However, the interrelationships between swimming performance and determinant variables are not always linear (Edelmann-Nusser et al., 2002; De Jesus et al., 2018;

Silva et al., 2007). As a result, once previous research has only concentrated on linear modelling methods, which may not be appropriate for explaining the characteristics and dynamics of complex movement in swimming, especially in distinguishing and predicting turning performance, it seems decisive to explore non-linear methods for better understanding what determines turning performance.

In sports applications, artificial intelligence (AI) and machine learning (ML) algorithms have been utilised successfully for sport injury prediction, game and performance analysis, and prediction of results (Van Eetvelde et al., 2021). The AI, which employs the non-linear features of artificial neural networks (ANN), is an attractive tool for analysing swimming results. The accuracy of using ANN to predict the relative contributions of factors related to swimming performance has already been discussed in freestyle swimming (Heazlewood, 2006; De Jesus et al., 2019; Stanula et al., 2012), 200 and 400 m individual medley (Silva et al., 2007), 50 and 800 m freestyle swimming (Maszczyk et al., 2012) and backstroke start (Carrard et al., 2020; De Jesus et al., 2018).

Swimming turn biomechanical studies of age-group swimmers have shown similarities between turning techniques (Blanksby et al., 2004; Chainok et al., 2021), performance variable relationships (Blanksby et al., 1998, 1996) and prediction of turning time using linear or multiple regression analysis (Blanksby et al., 1998, 2004; Ling et al., 2004). Again, exploring non-linear methods, like machine learning methods, may shade light into this issue. Machine learning algorithms belong to a subfield of AI, and they can provide decision-making directly from the data (Wei et al., 2021). Tree-based models are popular machine learning algorithms that can be used for either regression or classification based on probabilities (Van Eetvelde et al., 2021).

Moreover, the tree-based models could facilitate decision making, particularly when there are multiple chains of options (Maneiro et al., 2019). Thus, by evaluating which components have the highest effect in each model, well-performing models might offer an insight of the feature biomechanical characteristics related with 15 m turning performance when performing different backstroke to breaststroke turning techniques.

The current study aims to identify the biomechanical variables associated with 15 m turning performance while performing open, somersault, bucket, and crossover backstroke to breaststroke turning techniques. Additionally, it was also aimed to predict 15 m turning performance that was from the 7.5 m turn-in and 7.5 m turn-out distances using and comparing linear regression and tree-based machine learning models from selected features of kinematic-temporal, kinetic and hydrodynamic variables. It was hypothesized that the performance determinant factors of the backstroke to breaststroke turn techniques are specific of each one and that tree-based models would be able to produce more accurate turning performance prediction results compared to linear approaches.

Methodology

Participants

Eighteen volunteer age-group male and female swimmers provided written informed consent to participate in the study. Their main physic and training characteristics were: age 12.08 ± 0.17 years, stature 153.89 ± 3.30 cm, body mass 46.09 ± 3.49 kg, fat mass by bio impedance 17.70 ± 1.61%, sitting height 82.00 ± 2.00 cm, arm span 154.41 ± 4.14 cm, mean performance for the 200 m medley in 25 m pool of 188.06 ± 5.23 s, representing 55.72% ± 6.19% of world junior record and tanner stage 2–4 (self-evaluation), Approval for all experimental procedures was granted by the local university in accordance with the Helsinki Declaration.

Backstroke to breaststroke turns

Based on the FINA rules (SW 6.5 and 9.4; FINA, 2020), four backstroke to breaststroke turning techniques were considered. The complex movements of each technique, which specify body configuration and orientation during the approach, rotation and push-off phases, are presented in Figure 1(a–d). Key mechanical features in each backstroke to breaststroke turning technique were described using selected kinematic-temporal and kinetic (including hydrodynamic) variables.

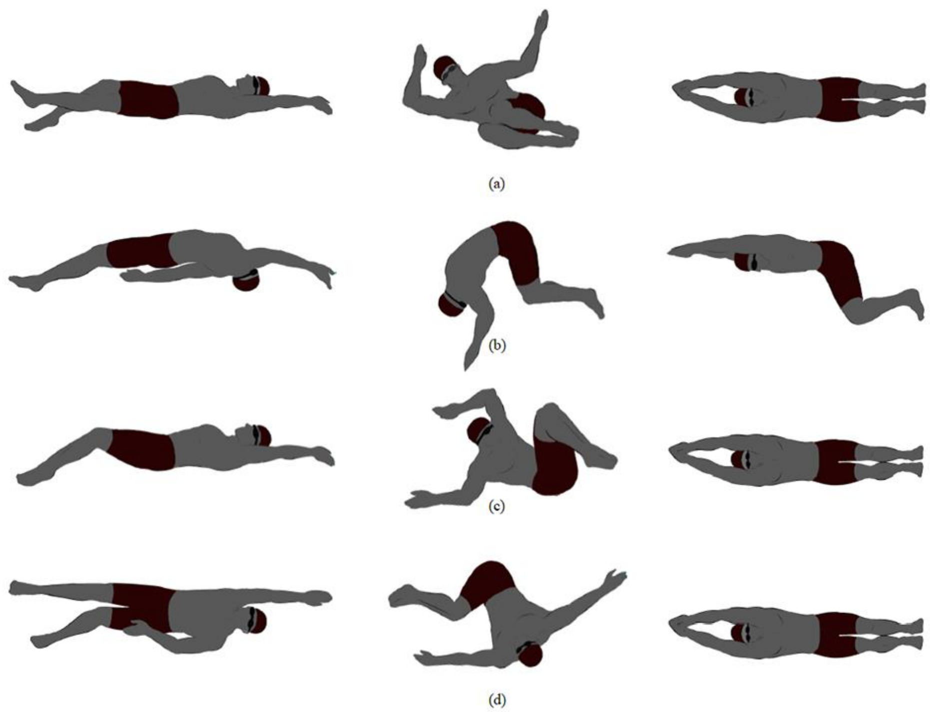

Figure 1. Representation of body configuration and orientation during approach, rotation and push-off phases: (a) open turn; (b) somersault turn; (c) bucket turn; (d) crossover turn.

Data collection

Age-group swimmers were assigned to 16 systematically increasing contextual interference sessions to facilitate skill learning (Guadagnoli and Lee, 2004). The swimmers followed a block schedule from the first to the fourth practice session, focusing on each turning technique for each session. Swimmers adopted a first serial-type schedule from the fifth to the eighth session, performing each turning technique twice (4 × 10 min) in each session. The second series of serial-type schedule of two 'laps' of (2 × 4 × 5 min) through all turning techniques was run from the ninth to the twelfth training sessions.

From the 13th to the 16th training sessions, each turning technique was subjected to a randomised equivalent number of trials. Testing took place one week after the intervention period. General characteristics, body composition, anthropometric and maturation stages were collected. Swimmers completed a standardised warm-up

(Chainok et al., 2021) before proceeding to a randomised series of 12 maximal trials, three for each turning technique, with three minutes rest between trials. The swimmers swam to the wall from a 15 m distance, rotating, gliding and swimming back to the 15 m mark. For the posterior analysis, the average values obtained for each variable of interest on the three trials of each turning technique were used.

The temporal and kinematic data were collected by automatically tracking 51 reflective markers with a dual-media twin motion capture system that included 12 land and 11 underwater cameras, recording at 100 Hz (Qualisys, Gothenburg, Sweden). The land and underwater cameras were mounted on opposite sides of the pool, covering a 10 m distance from the wall, with their respective lenses focused on the swimmers' trajectory. Each camera was configured, covers undesirable area s and eliminates sunlight reflections; (ii) adjust the exposure delay/flash time and marker threshold (values ranging from 0.0002 to 0.0012 s; 5 and 20, respectively); and (iii) filter and remove background sunlight.

Calibration began with a static L frame (positioned 5 m) to establish a simulated origin in the 3 D environment, followed by wand dynamic calibration with two markers set at 0.75 m inter-point-distance (covering expected performance volume) (De Jesus et al., 2018). In accordance with previous research, all camera calibration mean values were obtained with standard deviations of 0.008 m wand length (De Jesus et al., 2018).To assess the water level and orientation relative to the calibration frame origin, a short data acquisition was carried out. Kinetic data were collected using two tri-axial underwater force plates with a sampling frequency of 2000 Hz, mounted on the pool turning wall on a custom-built support (De Jesus et al., 2019).

A custom-built trigger box used manually generated starting commands based on a 5 V transistor– transistor logic signal to synchronis e kinetic and kinematic data (De Jesus et al., 2019). An inverse dynamics technique was used to evaluate the hydrodynamic data (D and CD) (as previously proposed by Vilas-Boas et al., 2010 and also used by L. Costa et al., 2015).The passive drag (D) during the first and second glides was calculated using the sacrum's velocity to time (v(t)) curve at each glide.

Data analysis

Qualisys Track Manager (QTM) software was used to automatically extract temporal and 3D kinematic data (Qualisys AB, Sweden). The 15 m turning time (7.5 m in + 7.5 m out) involved the following five intermediate backstroke to breaststroke turn phases: approach, acceleration, wall contact, gliding and stroke resumption. To choose an optimum cut-off frequency, residual analysis was performed using the software Acknowledge v. 3.9.0, which is built on the fast Fourier transform, and kinematic data were low-pass filtered using a digital filter with a cut-off frequency of 6 Hz (FIR—Window Blackman-61 dB) (Acqknowledge, BIOPACiopac Systems, Inc., Santa Barbara, CA, USA). Twenty -five temporal and kinematical variables were calculated: last stroke hand–wall distance, stroke length (SL) at last stroke, average SL during turn-in, last stroke rate (SR), average SR, touching depth, hand contact time, rotation time, total wall contact time, push-off time, tuck index, foot plant index, push-off velocity, first gliding distance, first gliding time, first gliding depth, transition distance, transition time, transition gliding depth, second gliding distance, second gliding time, second gliding depth, breakout distance, breakout time and 15 m turning time.

The kinetic data analysis involved the two key consecutive steps previously described (Mourão et al., 2016; De Jesus et al., 2019): (i) data acquisition of force and moment of force, plotting and saving strain readings of each tri-axial force plate were performed using routines written in LabView 2013 (SP1, NI, Austen, TX, USA) software; (ii) kinetic variables were obtained using a MATLAB routine (MathWorks Inc., Natick, MA, USA) using offset correction, data filtering with a fourth order zero-phase digital Butterworth filter with a cut-off frequency of 10 Hz, verification of the kinetic variables—force peak (the maximum value of the X, Y, Z force), wall contact time (WCT) and horizontal impulse were measured, and the average of three trials was taken into account for each turning technique observed. The hydrodynamic data were quantified using an inverse dynamics approach, taking into consideration each glide's sacrum marker velocity to time curve (v(t)). First, the sacrum marker trajectory was low pass filtered (fourth order Butterworth filter 190 with a 6 Hz cut-off frequency), then, using a MATLAB routine (MATLAB R2007a, MathWorks Inc.), the procedures defined by Vilas-Boas et al. (2010)

and used by L. Costa et al. (2015) were applied, allowing the acceleration to time curve to be obtained by differentiation and, subsequently, the mean drag force (D) at the first (D_1) and second (D_2) gliding position phases:

$$D = ma \qquad (1)$$

where m represents the swimmer's body mass and a represents the mean acceleration for each gliding as calculated by Newton's movement equation. The drag coefficient (C_D) was determined at the first (C_{D1}) and second (C_{D2}) gliding positions as follows:

$$C_D = 2D/\rho S v^2 \qquad (2)$$

where D is drag force, ρ is the water density (assumed to be 1000 kg/m3), v is the mean velocity for each gliding phase, and S is the body cross-sectional area calculated using planimetry based on scaled photographs as proposed by Vilas-Boas et al. (2010) and used by L. Costa et al. (2015). The selected temporal, kinematic, kinetic and hydrodynamic variables analysed in this study are presented in Table 1.

Table 1. The temporal, kinematic, kinetic and hydrodynamic variables for the study of the backstroke to breaststroke turns and their respective definition.

Variables	Definition
Last stroke hand–wall distance(m)	Middle finger to wall distance at the last upper limbs cycle length.
SL at last stroke (m)	The last upper limbs cycle length that was obtained by the horizontal displacement of the one upper limbs cycle.
Average SL during turn-in (m)	The average of the last five upper limbs cycle length obtained by the horizontal displacement of the one upper limbs cycle.
Last stroke SR(cycles · min^{-1})	The last upper limbs cycle dividing by the time duration of the one upper limbs cycle prior to the wall.
Average SR (cycles · min^{-1})	The average of the last upper limbs cycle dividing by the time duration of the one upper limbs cycle of the last five cycles to the wall.
Touching depth (m)	Depth at the hand beginning touching the wall.
Hand contact time (s)	Time at hand contact to the wall.
Hand peak X force (N)	The highest force applied while hand pushing to the left / right on the force plate during hand contact.
Hand peak Y force (N)	The highest force applied while hand pushing up or down on the force plate during hand contact.
Hand peak Z force (N)	The highest force applied perpendicular to the force plate during hand contact.

Table 1. The temporal, kinematic, kinetic and hydrodynamic variables for the study of the backstroke to breaststroke turns and their respective definition (continued).

Variables	Definition
Hand contact impulse (Z) (Ns)	The area under the perpendicular Z force-time curve during hand contact.
Rotation time (s)	The period of time between hand contacts to the feet contact during rotation phase.
Total wall contact time (s)	Total feet contact time to the wall.
Push-off time (s)	Time of feet with wall while hips move forward until the swimmer's feet had left the wall.
Tuck index (%)	Distance of right hip from the wall at the beginning of push-off divided by swimmer's leg length.
Foot plant index (%)	Depth of the foot plant on the wall at the beginning of push-off divided by swimmer's leg length.
Dominant peak_X push-off force : DPO_X (N)	The highest force applied while feet pushing to the left or right on the dominant force plate to the swimmer's feet had left the wall.
Dominant peak_Y push-off force : DPO_Y (N)	The highest force applied while feet pushing up or down on the dominant force plate during to the swimmer's feet had left the wall.
Dominant peak_Z push-off force : DPO_Z (N)	The highest force applied while feet horizontal pushing on the dominant force plate to the swimmer's feet had left the wall.
Dominant push-off impulse (Z) (Ns)	The area under the Z force-time curve during the foot push-off dominant force plate to the swimmer's feet had left the wall.
Non-dominant peak_X push-off force : DPO_X (N)	The highest force applied while feet pushing to the left or right on the non-dominant force plate to the swimmer's feet had left the wall.
Non-dominant peak_Y push-off force : DPO_Y (N)	The highest force applied while feet pushing up or down on the non-dominant force plate during to the swimmer's feet had left the wall.
Non-dominant peak_Z push-off force : DPO_Z (N)	The highest force applied while feet horizontal pushing on the non-dominant force plate to the swimmer's feet had left the wall.
Non-dominant push-off impulse (Z) (Ns)	The area under the Z force-time curve during the foot push-off non-dominant force plate to the swimmer's feet had left the wall.
Push-off velocity ($m \cdot s^{-1}$)	Resultant velocity of swimmer's sacrum at the swimmer's feet had left the wall.
First gliding distance (m)	Distance of sacrum travel from the swimmer's feet had left the wall to the first frame of transition phase.
First gliding time (s)	Time of swimmer's sacrum travel from the beginning of feet had left the wall to the first frame of transition.
First gliding depth (m)	An average of swimmer's sacrum depth during the gliding phase.

Table 1. The temporal, kinematic, kinetic and hydrodynamic variables for the study of the backstroke to breaststroke turns and their respective definition (continued).

Variables	Definition
Transition distance (s)	Distance of sacrum travel from the initial separation of the hands or starting dolphin kick until arms extended at sides of the body.
Transition time (s)	Time of swimmer's sacrum travel from the initial of hands separate or starting dolphin kick until the arms fully extended at sides of the body.
Transition gliding depth (m)	An average of swimmer's sacrum depth during transition phase.
Second gliding distance (m)	Distance of sacrum travel from the first frame of the arms fully extended at sides of the body to an instant which swimmer begins to move hands from the side of the body up.
Second gliding time (s)	Time of swimmer's sacrum travel from the first frame of the arms fully extended at the sides of the body to an instant which swimmer begins to move hands from side of the body up.
Second gliding depth (m)	An average of swimmer's sacrum depth during the second gliding phase.
Breakout distance (m)	Distance at which the swimmer's head breaks the surface for the first time.
Breakout time (s)	Time at which the swimmer's head breaks the surface for the first time.
First gliding drag force (N)	The passive drag force during the first gliding position that was assessed through inverse dynamics, following equation: $D = ma$.
Second gliding drag force (N)	The passive drag force during the second gliding position that was assessed through inverse dynamics, following equation: $D = ma$.
First gliding drag coefficient	The drag coefficient during the first gliding position that was assessed through inverse dynamics, following equation : $C_D = 2D / \rho S v^2$.
Second gliding drag coefficient	The drag coefficient during the second gliding position that was assessed through inverse dynamics, following equation : $C_D = 2D / \rho S v^2$.
15 m turning time (s)	15 m turning time is the turn time performance including 7.5 m time in and 7.5 m time out to 7.5 m out.

Statistical procedures

All the selected variables were checked for normality with the Shapiro–Wilk test. Group means, standard error of the mean s and 95% confidence intervals were computed. A one way analysis of variance (ANOVA) was used to observe differences in the selected kinematic–temporal, kinetic and hydrodynamic variables among the four different backstroke to breaststroke turning techniques. The ML method was developed and applied using Scikit-learn Python library. The performance modelling and prediction of the 15 m turning time in each turning technique were carried out from a total of 32 variables (16 kinematic, 12 kinetic and four hydrodynamic variables).

The performance modelling was carried out progressing through the following steps: (i) exploratory data analysis of four datasets corresponding to different turn techniques, with the different features and correlations among them also explored using heat maps and scatter plots of the most correlated; (ii) visualisation of the principal component analysis (PCA) was performed for all datasets; (iii) model creation through model comparison in conjunction with a hyper parameter randomised search, examining two linear models and seven different tree-based machine learning models: Lasso and Ridge (linear models), a single decision tree (TREE), a random forest algorithm (RF), adaboost (ABST), gradient boosting (GBST), extra trees (XTREE), extreme gradient boosting (XGBST) and quantile random forest (QRF); (iv) the model was chosen based on the values of the coefficient of determination (R2) and mean squared error (MSE) using leave-one-out cross validation (LOOCV), 5-fold cross-validation and 10-fold cross-validation. The value of the features for each dataset was determined using the SHAP (SHapley Additive exPlanations) method, with the best models in the test hold-out for the linear and tree-based models.

Results

Descriptive analysis and results from ANOVA test on selected temporal, kinematic, kinetic and hydrodynamic variables for each backstroke to breaststroke turning technique are presented in Table 2. A one-way ANOVA indicated that the turning techniques had no significant main impact on 15 m turning time ($F_{3, 208} = 0.24$; $p = 0.87$). Furthermore, no significant differences were observed for the approach phase variables, rotation time, breakout time and hydrodynamic variables.

The majority of differences were observed in the kinetic and kinematic variables during the wall contact phase, as well as in the gliding depth during the turn-out phase. The four datasets were analysed based on the different turns, being them: open, somersault, bucket and crossover. Initially, each dataset has 40 features and the target, which is the ‘total turn time at 15 m’. Since the label of the datasets is time-related, one should remove the temporal covariates because of their high correlation with the time-based target. Indeed, a first attempt of modelling showed that the best predictors of the 15 m performance were the 7.5 m-in and the 7.5 m-out times.

Therefore, the hand contact, rotation, wall contact, push-off, first gliding, transition, second gliding and breakout time temporal covariates present in all the datasets were not considered. All the four datasets were normalised so that all the attributes or features have a mean equal to 0 and a standard deviation equal to 1. The target distribution is normalised between 0 and 1 and the distributions of the different datasets are diversified. Figure 2 presents the heatmaps for all the datasets included characteristics that have a direct relationship with others. A scatter plot of the most correlated features is shown based on the features that stand out in the heatmaps evaluation (Figure 2). The PCA was then performed in all the datasets to visualise the samples considering all the features available to explain at least 95% of the variance (Figure 3). The variance of seven principal components are necessary for the open and crossover datasets while six and five principal components are required for the bucket and somersault datasets, respectively (Figure 4).

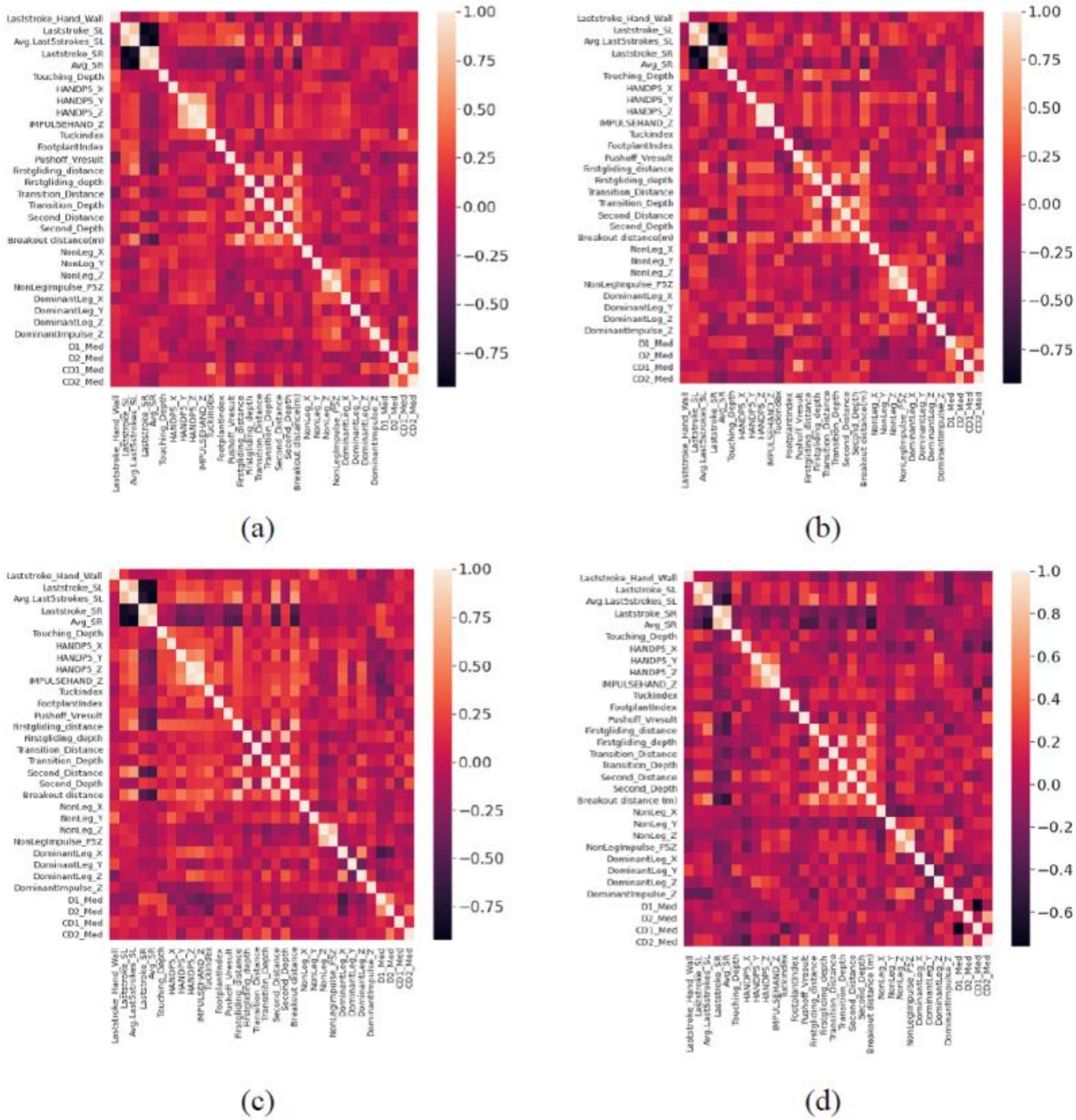

Figure 2. Features correlation heatmaps. Notice that each dataset has a different group of features which correlate differently among each other. The heatmaps for the (a) open, (b) somersault, (c) bucket, and (d) crossover datasets are depicted.

Table 2. Descriptive analysis and results from ANOVA test on all predicted variables for the four backstroke to breaststroke turning technique.

Parameters	Open	Somersault	Bucket	Crossover	Total
Last stroke hand–wall distance (m)	0.46 ± 0.25	0.57 ± 0.25	0.52 ± 0.25	0.48 ± 0.27	0.51 ± 0.26
SL at last stroke (m)	1.64 ± 0.28	1.55 ± 0.28	1.64 ± 0.31	1.63 ± 0.30	1.61 ± 0.30
Average SL during turn-in (m)	1.69 ± 0.20	1.66 ± 0.18	1.71 ± 0.22	1.69 ± 0.20	1.69 ± 0.20
Last stroke SR (cycles · min^{-1})	36.83 ± 7.98	38.89 ± 8.24	36.39 ± 8.55	36.85 ± 8.03	37.26 ± 8.18
Average SR (cycles · min^{-1})	36.01 ± 6.79	36.38 ± 5.81	35.23 ± 6.89	36.00 ± 6.83	35.93 ± 6.55
Touching depth (m)	0.18 ± 0.09^{s,c}	0.36 ± 0.12^{o,b,c}	0.16 ± 0.09^{s}	0.13 ± 0.05^{o,s}	0.21 ± 0.13
Hand contact time (s)	0.50 ± 0.21^{b,c}	0.49 ± 0.18^{b,c}	0.59 ± 0.16^{o,s,c}	0.37 ± 0.15^{o,s,b}	0.49 ± 0.19
Hand peak X force (N)	1.60 ± 0.32^{c}	1.61 ± 0.23^{c}	1.68 ± 0.26^{c}	1.50 ± 0.22^{o,s,b}	1.60 ± 0.27
Hand peak Y force (N)	9.35 ± 2.56^{b}	8.48 ± 1.93^{b}	17.37 ± 3.33^{o,s,c}	9.05 ± 2.22^{b}	10.78 ± 4.32
Hand peak Z force (N)	26.92 ± 24.00	42.58 ± 21.82^{c}	41.86 ± 22.89^{c}	21.89 ± 16.11^{s,b}	32.87 ± 12.85
Hand contact impulse (Z) (Ns)	14.76 ± 4.79	23.40 ± 4.41^{c}	24.07 ± 5.63^{c}	8.61 ± 1.53^{s,b}	17.46 ± 6.95
Rotation time (s)	1.25 ± 0.18	1.28 ± 0.22	1.32 ± 0.24	1.33 ± 0.34	1.30 ± 0.23
Total wall contact time (s)	0.55 ± 0.19^{c}	0.57 ± 0.18^{c}	0.53 ± 0.12^{c}	0.64 ± 0.20^{o,s,b}	0.57 ± 0.18
Push-off time (s)	0.39 ± 0.16^{c}	0.43 ± 0.13^{b}	0.37 ± 0.08^{s,c}	0.45 ± 0.14^{o,b}	0.41 ± 0.14
Tuck index	0.71± 0.15^{b}	0.75 ± 0.10	0.76 ± 0.11^{o}	0.73 ± 0.13	0.73 ± 0.13
Foot plant index	0.59 ± 0.19^{s,c}	0.68 ± 0.19^{s,b,c}	0.55 ± 0.18^{s}	0.50 ± 0.16^{o,s}	0.58 ± 0.19
NPO_X (N)	1.64 ± 0.19	1.65 ± 0.21	1.67 ± 0.17	1.59 ± 0.23	1.64 ± 0.20
NPO_Y (N)	19.41 ± 8.25^{s,c}	15.30 ± 8.34^{o,b}	21.12 ± 10.67^{s,c}	13.23 ± 5.41^{o,b}	17.23 ± 8.65
NPO_Z (N)	49.36 ± 24.99^{b,c}	45.81 ± 36.63^{c}	36.37 ± 20.59^{o,c}	62.84 ± 34.59^{o,b,c}	48.96 ± 34.14
NPO_ Impulse (Z) (Ns)	34.02 ± 25.07^{s,b}	21.90 ± 15.47^{o,c}	17.55 ± 8.44^{o,c}	31.34 ± 25.54^{s,b}	26.70 ± 21.33
DPO_X (N)	21.66 ± 16.03^{s,b,c}	12.99 ± 5.36^{o,c}	14.74 ± 8.63^{o,c}	8.03 ± 3.24^{o,s,b}	14.64 ± 11.14
DPO_Y (N)	64.93 ± 37.25	37.27 ± 20.17^{o,b,c}	70.09 ± 33.10^{s,c}	56.06 ± 27.76^{s,b}	56.86 ± 35.05
DPO_Z (N)	145.45 ± 76.20^{b}	140.090 ± 65.50^{c}	194.40 ± 109.14^{o,s,c}	141.44 ± 13.06^{b}	153.65 ± 78.90
DPO_ impulse (Z) (Ns)	53.07 ± 30.50	52.03 ± 33.61	57.75 ± 39.48	49.92 ± 33.12	53.04 ± 33.87
Push-off velocity (m·s^{-1})	2.03 ± 0.31	2.02 ± 0.33	2.01 ± 0.30	2.17 ± 0.38	2.06 ± 0.33
First gliding distance (m)	2.41 ± 0.56	2.60 ± 0.70	2.46 ± 0.67	2.43 ± 0.69	2.47 ± 0.65
First gliding time (s)	1.21 ± 0.42	1.34 ± 0.53	1.31 ± 0.45	1.29 ± 0.40	1.28 ± 0.45
First gliding depth (m)	0.48 ± 0.09^{s,b}	0.72 ± 0.15^{o,b,c}	0.54 ± 0.13^{o,s}	0.48 ± 0.13^{s}	0.55 ± 0.16
Transition distance (m)	1.09 ± 0.20	1.08 ± 0.24	1.09 ± 0.16	1.10 ± 0.21	1.09 ± 0.20
Transition time (s)	0.99 ± 0.22	0.92 ± 0.20	0.96 ± 0.18	0.96 ± 0.19	0.96 ± 0.20
Transition gliding depth (m)	0.62 ± 0.14^{s}	0.86 ± 0.19^{o,b,c}	0.67 ± 0.19^{s}	0.64 ± 0.17^{s}	0.70 ± 0.20
Second gliding distance (m)	0.81 ± 0.26	0.85 ± 0.30	0.88 ± 0.28	0.87 ± 0.30	0.85 ± 0.28
Second gliding time (s)	0.78 ± 0.27	0.83 ± 0.36	0.86 ± 0.32	0.85 ± 0.34	0.82 ± 0.32
Second gliding depth (m)	0.62 ± 0.17^{s}	0.76 ± 0.18^{o,b,c}	0.62 ± 0.18^{s}	0.62 ± 0.17^{s}	0.65 ± 0.19
Breakout distance (m)	5.97 ± 0.87	6.12 ± 1.00	6.03 ± 0.93	6.02 ± 0.99	6.04 ± 0.94
Breakout time (s)	4.84 ± 0.94	5.00 ± 1.03	4.83 ± 0.97	4.79 ± 0.98	4.86 ± 0.98
D_1 (N)	-35.86 ± 9.96	-38.27 ± 6.53	-40.10 ± 11.28	-39.19 ± 14.42	-38.20 ± 13.26
D_2 (N)	-61.81 ± 25.70	-64.40 ± 27.25	-61.80 ± 25.83	-69.63 ± 28.84	-64.37 ± 26.91
C_{D1}	-0.74 ± 0.16	-0.72 ± 0.29	-0.74 ± 0.34	-0.81 ± 0.45	-0.75 ± 0.32
C_{D2}	-1.14 ± 0.44	-1.12 ± 0.37	-1.16 ± 0.54	-1.27 ± 0.55	-1.17 ± 0.48
15 m turning time (s)	15.10 ± 1.55	14.99 ± 1.50	14.88 ± 1.60	15.09 ± 1.60	15.03 ± 1.53

o,s,b and c: significantly different from open, somersault, bucket and crossover turn ($p < 0.05$).

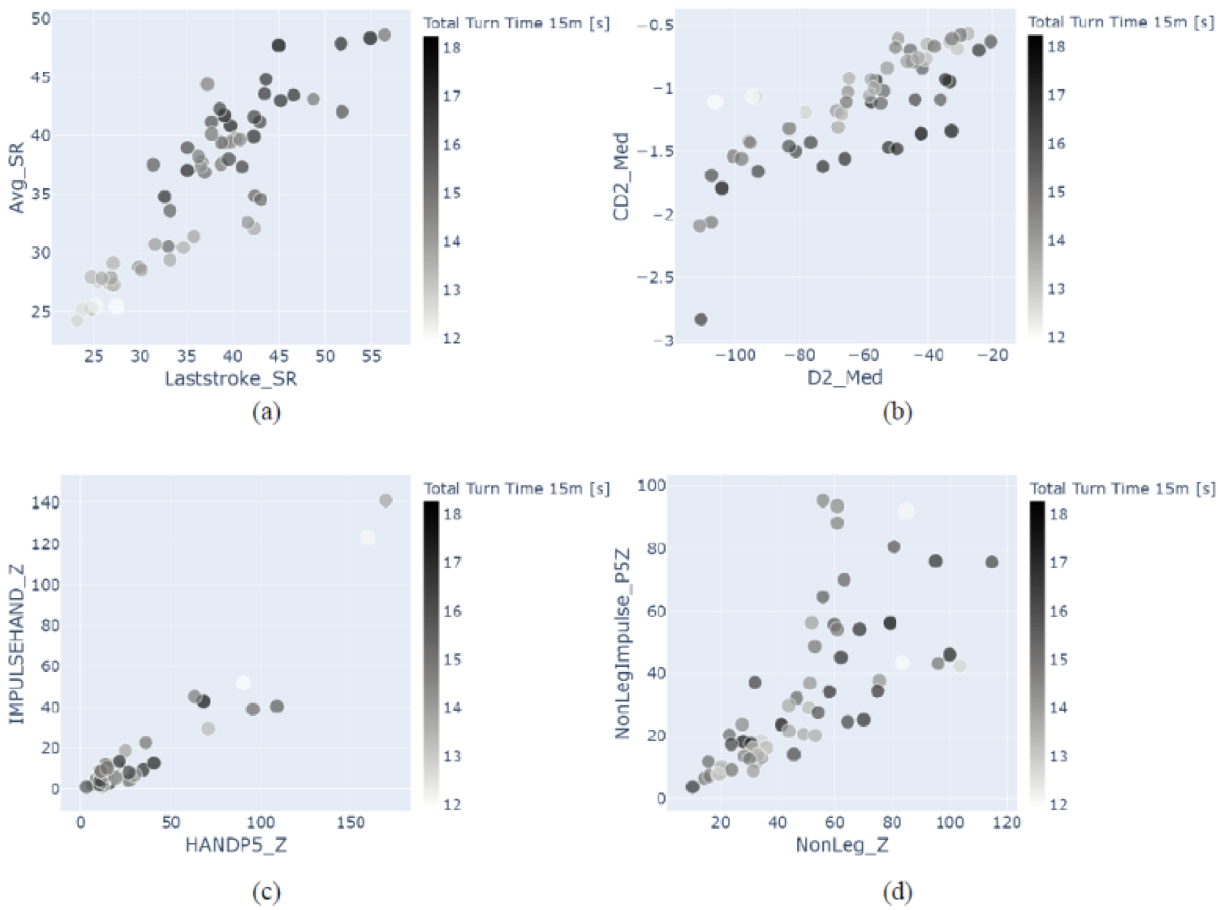

Figure 3. Plots of the most correlated features in 2D space for the open dataset. The plots are disposed for features of: (a) ‘Avg_SR’ and ‘Laststroke_SR’; (b) ‘CD2_Med’ and ‘D2_Med’; (c) ‘IMPULSEHAND_Z’ and ‘HANDP5_Z’; and (d) ‘NonLegImpulse_P5Z’ and ‘NonLeg_Z’. Notice that the colour of each sample is related to a grey colour map. Higher values are closer to the black colour while lower values are closer to the white colour.

Considering the MSE and R2 results, the linear models obtained the greatest results in open, somersault and bucket turn, while the best model of crossover was found in the tree-based model. The best models were obtained in Lasso linear model of the LOOCV method in open turn (MSE = 0.011; R^2 = 0.825) and in the somersault turn (MSE = 0.011; R^2 = 0.734), while the best model was obtained in Ridge of the LOOCV method (MSE = 0.016; R^2 = 0.763) for the bucket turn. The best models were obtained in ABST tree-based model of the LOOCV method in crossover turn (MSE = 0.016; R^2 = 0.644) (Table3).

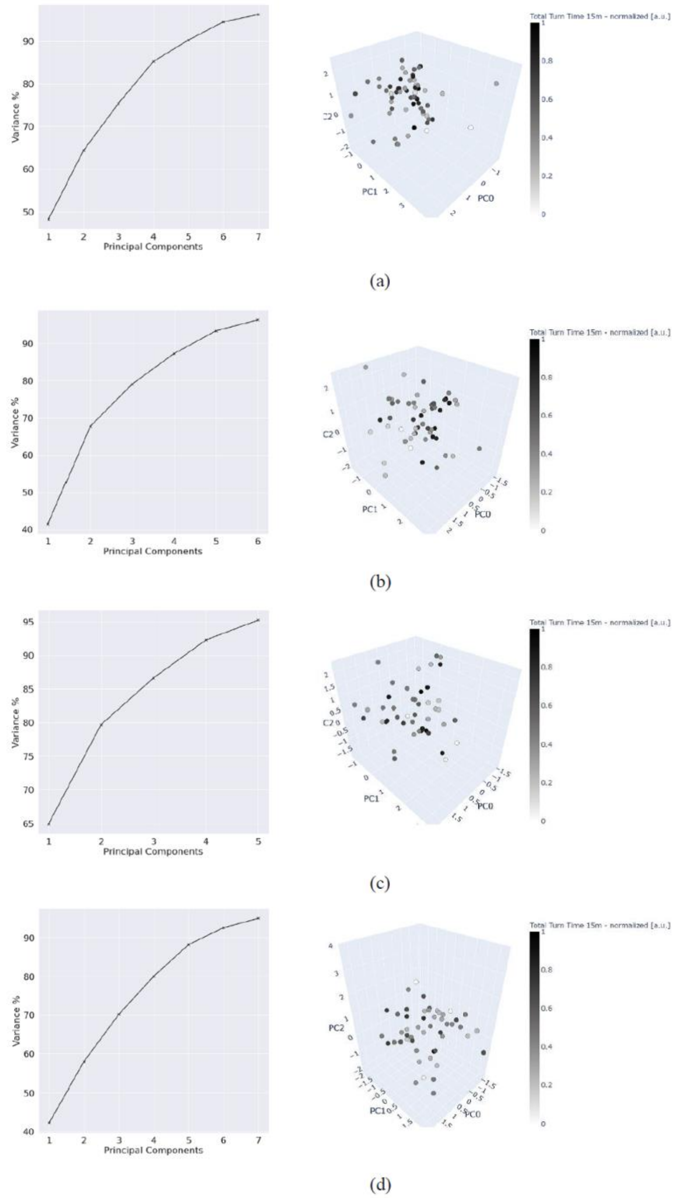

Figure 4. Explained variance and 3D plot of the first three PCs of PCA analysis. The (a), (b), (c), and (d) are the explained variance and 3D plots are depicted for the open, somersault, bucket and crossover datasets respectively.

Table 3. Results of the three types of cross-validation of the two linear models and seven decision tree in each turning technique.

Leave-one-out cross validation								
Turns	Open		Somersault		Bucket		Crossover	
Based Model	MSE	R^2	MSE	R^2	MSE	R^2	MSE	R^2
LASSO	**0.011**	**0.825**	**0.016**	**0.734**	0.019	0.725	0.021	0.537
RIDGE	0.013	0.778	0.020	0.674	**0.016**	**0.763**	0.019	0.571
TREE	0.020	0.667	0.026	0.577	0.025	0.646	0.018	0.590
RF	0.020	0.672	0.027	0.551	0.025	0.636	0.019	0.574
ABST	0.015	0.743	0.027	0.552	0.022	0.680	**0.016**	**0.644**
GBST	0.019	0.684	0.026	0.571	0.021	0.697	0.020	0.546
XTREE	0.018	0.706	0.026	0.571	0.018	0.738	0.018	0.596
XGBST	0.016	0.734	0.027	0.555	0.023	0.669	0.018	0.596
QRF	0.020	0.672	0.027	0.551	0.025	0.636	0.019	0.574
5-fold cross-validation								
Turns	Open		Somersault		Bucket		Crossover	
Based Model	MSE	R^2	MSE	R^2	MSE	R^2	MSE	R^2
LASSO	**0.014**	**0.738**	**0.018**	**0.620**	0.024	0.627	0.024	0.449
RIDGE	0.016	0.702	0.021	0.554	**0.018**	**0.700**	0.023	0.448
TREE	0.020	0.619	0.028	0.415	0.034	0.373	0.023	0.418
RF	0.020	0.647	0.024	0.583	0.027	0.533	**0.021**	0.490
ABST	0.016	0.715	0.026	0.524	0.028	0.531	0.028	0.335
GBST	0.017	0.682	0.029	0.486	0.021	0.650	0.022	**0.493**
XTREE	0.020	0.657	0.033	0.420	0.026	0.593	0.023	0.447
XGBST	0.018	0.656	0.028	0.515	0.023	0.625	0.025	0.396
QRF	0.020	0.647	0.024	0.583	0.027	0.533	**0.021**	0.490
10-fold cross-validation								
Turns	Open		Somersault		Bucket		Crossover	
Based	MSE	R^2	MSE	R^2	MSE	R^2	MSE	R^2
LASSO	**0.011**	**0.715**	**0.015**	**0.544**	0.020	0.429	0.022	-0.048
RIDGE	0.014	0.661	0.019	0.405	**0.017**	**0.498**	0.024	-0.163
TREE	0.022	0.557	0.028	-0.093	0.035	0.255	0.027	-0.234
RF	0.020	0.561	0.028	0.168	0.028	0.302	0.021	0.155
ABST	0.016	0.630	0.030	0.253	0.026	0.385	0.021	-0.135
GBST	0.019	0.601	0.029	0.242	0.019	0.559	**0.020**	-0.070
XTREE	0.019	0.578	0.034	0.199	0.022	0.481	0.023	-0.313
XGBST	0.017	0.625	0.029	0.278	0.022	0.461	0.025	-0.177
QRF	0.020	0.561	0.028	0.168	0.028	0.302	0.021	**0.155**

The bar plot and a bee swarm plot (Figure 5) incorporate with the spider chart (Figure 6), representing, respectively, the mean (normalised between 0 and 1) of the absolute SHAP values and the distribution of SHAP values based on each individual training sample. The most important features for the open and somersault turn were average stroke rate, average SL during turn-in, D_2, C_{D2}, second gliding depth and breakout distance. The most important features for the bucket turn were average stroke rate, transition gliding depth and non-dominant peak_Y push-off force (NPO_Y). The two most important features for the crossover turn were average SL during turn-in and breakout distance.

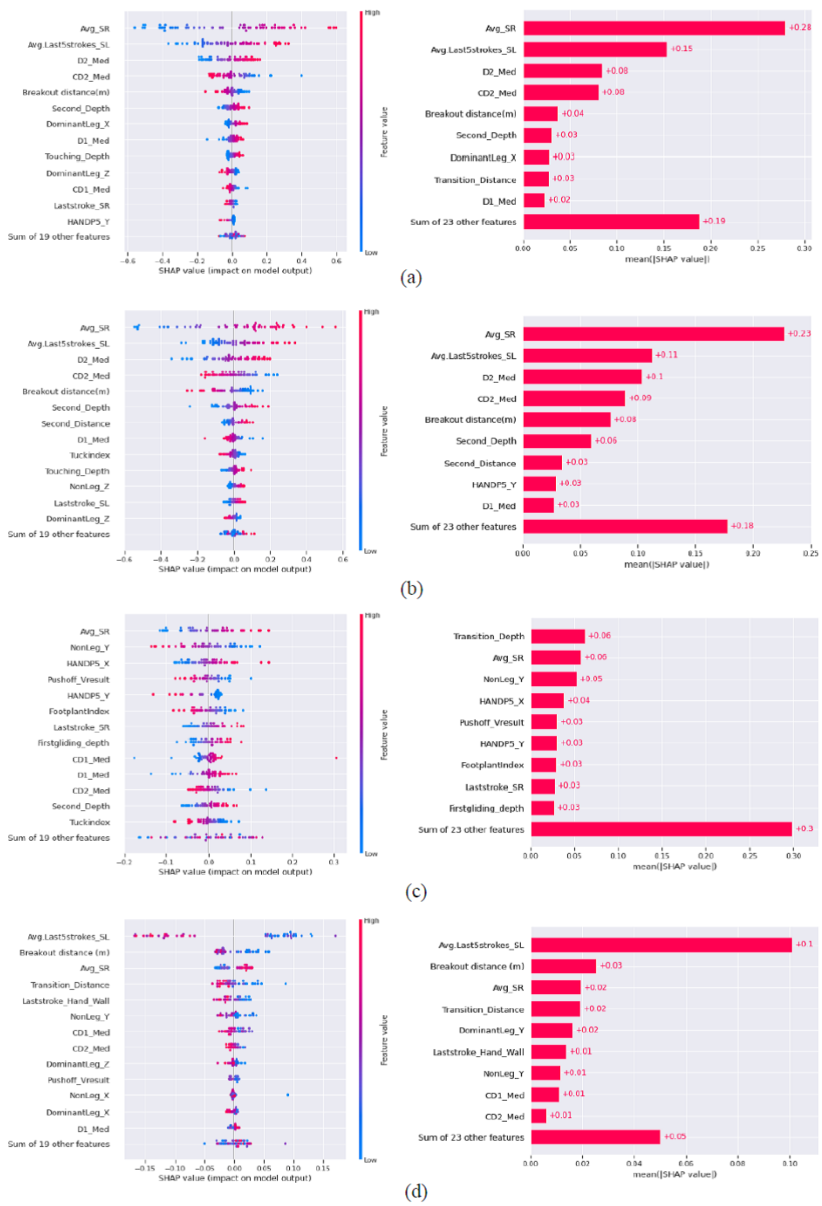

Figure 5. Relative importance of features bar plots and bee swarm charts. The (a), (b), (c) and (d) are the bar plots and bee swarm charts are depicted for the open, somersault, bucket and crossover datasets respectively.

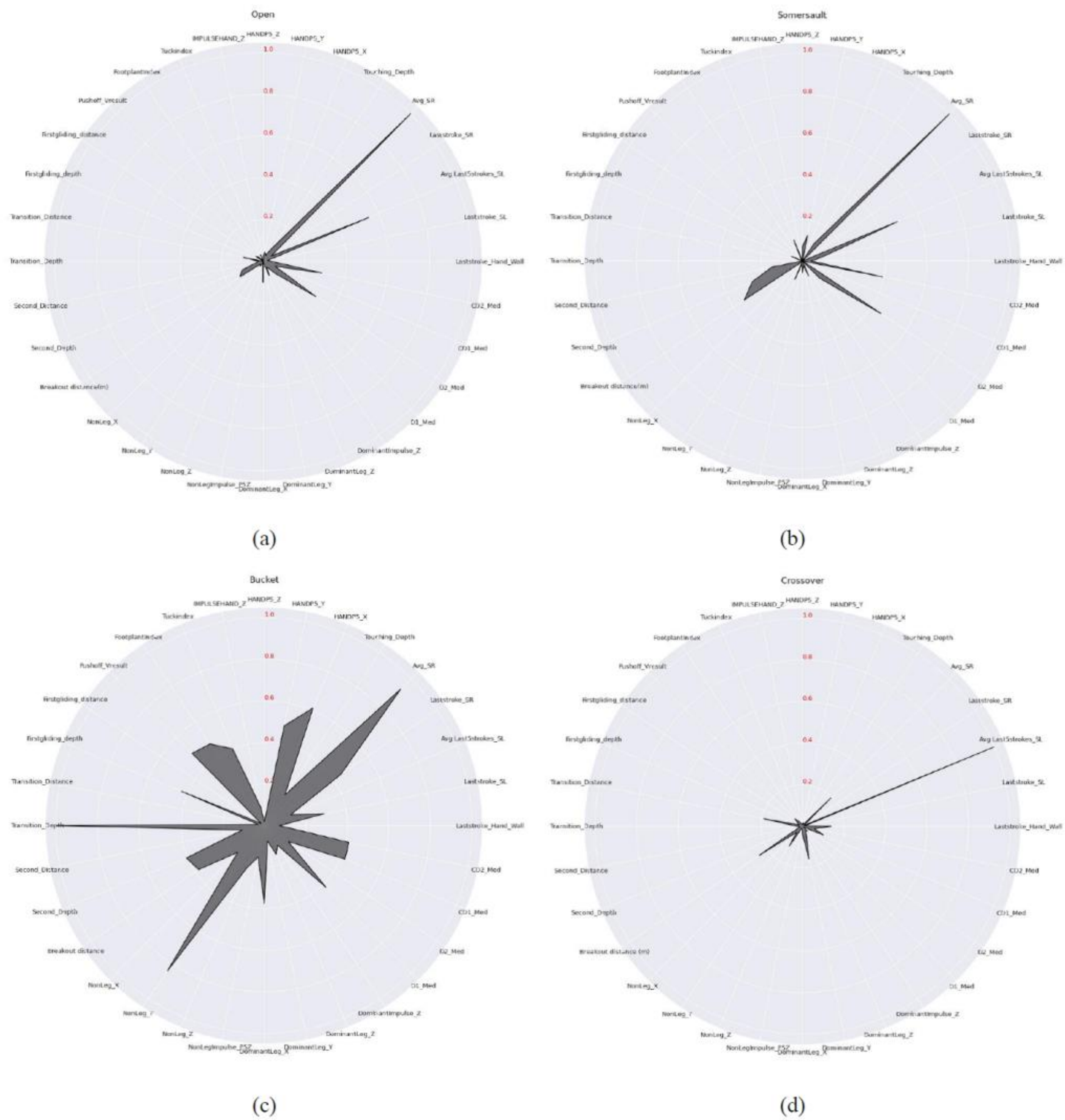

Figure 6. Spider charts for the normalised SHAP mean absolute values for all the features of the datasets (a) open, (b) somersault, (c) bucket, and (d) crossover.

Discussion

The purposes of the current study were to identify the biomechanical variables associated with 15 m turning performance while performing different backstroke to breaststroke turning techniques, such as the open, somersault, bucket, and crossover and to predict 15 m turning performance that was summarised from the 7.5 m turn-in and 7.5 m turn out distances using and comparing linear and tree-based machine learning models from selected features of kinematic-temporal, kinetic and hydrodynamic variables. Overall, the Lasso was the best prediction model validated using LOOCV in open and somersault turns, and the Ridge was the best in bucket turn, while the ABST tree-based LOOCV model was the best predictor in crossover turn. Age-group swimmers should focus on the relevant biomechanical contributions through the improvement of symmetrical contributions between turn-in and turn-out performance, as well as insights for specific interventions to improve in each backstroke to breaststroke turning technique.

From a perspective of deterministic model in biomechanics research, selecting a specific approach and suitable model to determine the relationships between complex movements is challenging (Chow and Knudson, 2011). From this perspective, experimental research on swimming turn performance has shown that a large number of variables, rather than a single variable, will directly influence turning performance (Chainok et al., 2021; Marinho et al., 2020; Nicol et al., 2019; Pereira et al., 2015) and the relationship between biomechanic variables is not always linear (Blanksby et al., 1998, 1996). Consequently, using two linear models (Lasso and Ridge) and ML algorithms using seven tree-based models (TREE, RF, ABST, GBST, XTREE, XGBST and QRF) to predict the relative contributions of factors associated with swimming turn performance could firstly reduce the model complexity and multi-collinearity and provide insights into the characteristics and interrelations among collections of the predicting variables of the four backstroke to breaststroke turning techniques performance.

In general, different predictive analyses based on machine learning are used to evaluate and estimate the one that gives the best predictive performance (Jovanovic, 2019). Besides analysing backstroke to breaststroke biomechanical determinants of different techniques, the main novelty of this research was predicting 15 m turning performance through both linear models (Lasso and Ridge) and ML algorithms using tree-based models (TREE, RF, ABST, GBST, XTREE, XGBST and QRF) from selected features on the kinematic-temporal, kinetic and hydrodynamic variables. The Lasso was the best model using LOOCV in open and somersault turns, while the Ridge was the best model using LOOCV in bucket turn. The difference between the Ridge and the Lasso regression models is that the penalty in the Ridge is the sum of squares, whereas the penalty in the Lasso model is the sum of absolute values (Tibshirani, 1996). Our findings appear to be well substantiated by Yarkoni and Westfall (2017) indicating that the Lasso and the Ridge regressions were very useful in situations when there are a lot of predictors, and it is easy to overfit the model. In the current study, 32 variables were used to predict 15 m turning performance and they might very well be accountable for this finding. We believe that our method could be probably usefully employed in predicting turning performance, particularly in the dynamics of complex movement evolving a large number of factors, as previously done in ventral start performance (Silveira et al., 2018).

Differently from the other turns datasets, the best model for the LOOCV in the crossover dataset is ABST tree-based model. In general, the best models achieve reasonable to satisfying results ranging from 0.644 (Crossover for LOOCV) to 0.825 (Open for LOOCV) R^2 values, demonstrating that a data-driven model can be trained with the measured features and predict 15 m turning performance. In spite of regression analysis is usually affected by multicollinearity, predicting of crossover turning performance can be challenging because multicollinearity does not affect the overall fit or the predictions of the model (Kutner et al., 2005). The evidence from this study points towards the idea that structure of proposed models based on ML algorithms using seven tree-based models with k-fold cross-validation is an efficient implementation for sports performance analysis and advantageous comparing to regression predictive modelling (Chen and Guestrin, 2016; Zhang et al., 2021).

In the turning zone, changing either higher or lower in stroking characteristics associated with speed, SR and SL have been interpreted as a matter of pacing strategy, swimming expertise (Seifert et al., 2005) and proper execution in compliance with the rules and regulations (Hellard et al., 2008). The remarkable finding from the exploratory data is that age-group swimmers should be focused on maintaining an approaching speed that is consistent with high SR and SL values (Blanksby et al., 2004; Seifert et al., 2005). These finding favourably compare with Nicol et al. (2019), indicating that turn-in time was the strongest correlated variable to total turn time in freestyle. Besides, this finding supports previous suggestion that swimmers should maintain swimming speed and momentum into the wall while setting the body in the correct position to turn during the approach phase (Blanksby et al., 2004; Webster et al., 2011).

Considering the biomechanical variables associated with 15 m turning performance in open and somersault turns, it seems that turning performance may necessarily require a good combination of turn-in and turn-out performance. The findings from this study in age-group swimmers support the possibility that, by improving kinaesthetic awareness in supporting the perception and acquisition of backstroke approach execution, turn-in performance can be improved. Regarding to turn-out performance, the main consideration should be given to optimising propulsion force, gliding depth and distance, without decreasing velocity (Termin and Pendergast, 1998). This finding emphasis e the importance of hydrodynamic characteristics during turn-out phase, meaning that age-group swimmers should perform the streamline posture with a proper underwater stroking that could be directly beneficial for maximising the distance of turn-out performance (Havriluk, 2005; Naemi et al., 2010). In addition, the predicting model was in line with previous research, suggesting that swimmers should glide at approximately 0.40–0.60 m depth to maximise drag reduction and optimise pull-out strategy, which have been previously demonstrated to improve turning performance (Chainok et al., 2021; Lyttle et al., 1998; Termin and Pendergast, 1998).

As pointed out by the previous studies, optimal approaching speed together with the kinematic factors at wall contact and optimal gliding strategy could directly influence the turning performance (Blanksby et al., 2004; Chainok et al., 2021; Pereira et al., 2015; Vilas-Boas et al., 2010). This is in complete agreement and corroborated the results in bucket turn conclusion that the most relevant variables to 15 m turning performance were average SR, transition gliding depth, and non-dominant peak Y force (NPO Y). In the meantime, results obtained during the wall contact phase were somehow disappointing, once, unexpectedly, results revealed no relationship between kinetic variable at wall contact phase and 15 m turning performance. The reason for this might be that the peak perpendicular force (open turn: 145.45 ± 76.20 N; somersault turn: 140.09 ± 65.50 N) was relatively smaller compared to those obtained for the butterfly turn (744.4 ± 327.1 N; Ling et al., 2004), the tumble turn (693.4 ± 228.1 N; Blanksby et al., 1996) and the breaststroke turn (557.41 ± 109.61 N; Blanksby et al., 2004) in age-group swimmers.

Higher medio-lateral (X) and up or down (Y) pushing forces have previously been suggested as relevant kinetic characteristics at wall contact, which may directly reflect on horizontal push-off force and impulse (Blanksby et al., 2004; Pereira et al., 2015). The high contribution of the vertical push-off force may be negatively correlated with turnout performance (Blanksby et al., 2004).The peak Y force in the present study tended to be higher than the study of rollover backstroke by about (20–22%) in bucket turn (Blanksby et al., 2004). Our findings show that symmetrical contributions and push-off orientation play an essential role in applying push-off force and propulsive impulse to achieve a high push-off velocity, as well as increasing underwater pull-out and gliding efficacy (Havriluk, 2005; Naemi et al., 2010; Puel et al., 2012). These data suggest that the bucket turn, in which the swimmer pushes against the wall on one side, may need a symmetric powerful extension push-off force rather than relying on the laterality preferred lower limb.

The key parameter included in the ABST tree-based machine -learning models in crossover turn were average SL during turn-in and breakout distance. This outcome has increased our confidence in turning performance, which will require a good combination and symmetrical contributions between turn-in and turn-out phases. Similarly to the other turns, it would appear that maintaining approaching speed was of greater importance for the turn-in performance. For the turn-out performance, the inclusion of breakout distance was consistent with previous research findings indicating that underwater gliding efficacy and an optimised pull-out strategy are also of high importance (Chainok et al., 2021; Naemi et al., 2010). Surprisingly, the rotation and wall contact phase variables had no effect on crossover turn performance in ABT tree-based models. Notably, this was attributed to a slightly slower rotating time (1.33 s) when completing the complicated crossover, which may have a direct influence on the lower generation of a push-off force (141.44 ± 13.06 N) and impulse (49.92 ± 33.12 Ns). As a result, strengthening the approaching speed in conjunction with an extremely fast rotation, efficacy at the wall contact phase, hydrodynamic underwater posture and glide, and an ideal pull-out strategy are all becoming increasingly important to turning performance (Chainok et al., 2021; Pereira et al., 2015; Vilas-Boas et al., 2010).

Finally, it is plausible that a number of limitations might be able to have influenced the results obtained, which should be addressed in future research. As it might have been expected, the quality and size of the data sets are important when seeking to develop ML techniques and feature combinations to find the most appropriate model, their specific interactions and enhance our understandings of sports performance. In terms of sample size, eighteen age-group swimmers were pooled to provide a sufficient sample size for assessment without considering gender into account. Consequently, future research with a larger sample size is required to understand the differences between male and female swimmers. Furthermore, it should be noted that the results of the machine learning methods prediction model are only appropriate for age-group swimmers and should not be generalized to other swimming performance levels. This means that swimmers who have different performance level from the regional age-group swimmers of the current study, such as national and international swimmers, might show different results.

Practical implications

The two linear models (Lasso and Ridge) and ML algorithms using seven tree-based models approach (TREE, RF, ABST, GBST, XTREE, XGBST and QRF) discussed here are significant steps toward s identifying the features and interrelationships of biomechanical predictors on four backstroke to breaststroke turning performance techniques in age-group swimmers. The Lasso and Ridge linear models and ABST tree-based model indicated the most relevant variables to backstroke to breaststroke turning performance in each technique and different groups of variables were included in the model depending on the turning technique. Despite the fact that optimum turning performance was very similar, symmetrical contributions between turn-in and turn-out depicted the most significant characteristics, and different techniques should be discussed based on the findings of this analysis. Coaches should pay attention not only to temporal data, but also to kinematic, kinetic and hydrodynamic variables that have a direct influence on 15 m backstroke to breaststroke turn performance. For all turning techniques, emphasis should be placed on approaching speed determined by SR and SL in conjunction with proper gliding posture and pull-out performance. Furthermore, the rotation performance and kinetic and kinematic performance at wall contact, which has reinforced the relevance of the pushing and turn-out phase for an effective backstroke to breaststroke turning performance, should be addressed, especially in age-group swimmers.

Conclusion

The linear and tree-based machine learning models allowed us to identify the highly realistic models of backstroke to breaststroke turn performance based on comprehensive temporal, kinematic, kinetic (including hydrodynamic) variables. The accuracy of the predictive model in each backstroke to breaststroke turn technique substantiates previous findings in the literature that turning performance requires symmetrical contributions between turn in and turn out phases. According to the findings of this age-group study, turning performance appears to be more dependent on developing approaching speed in conjunction with kinematic at wall contact efficacy, as well as the appropriate gliding posture and pull-out strategy. When coaches are focusing on technical adjustments for consistent practice and delivery of specific training intervention programs, supervised learning models using linear and decision tree-based models could be considered a holistic approach to evaluating the complexity of turning performance, particularly among age-group swimmers.

CHAPTER 6.

Biomechanical analysis of the backstroke to breaststroke turns in age-group swimmers: An intervention study

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Abstract

This study aimed to examine four different breaststroke to breaststroke turning techniques before and after a four-week intervention programme that systematically increased contextual interference in age-group swimmers. Ten girls and ten boys (12.05 ± 1.24 years old), belonging to the same swimming team and with regular competitive participation in regional events, participated in this study. Swimmers performed three trials of each turn and were monitored using 23 Qualisys cameras (12 aerial and 11 underwater cameras) and two underwater tri-axial force plates. The 15 m turning time for all turns improved significantly over the intervention study period ($p < 0.01$) with percentage improvements of 5.3, 5.1, 4.9 and 4.8 % for the somersault turn, open turn, crossover turn and bucket turn, respectively. The highest significant improvement of mean time spent between pre- and post-intervention was found in the rotation phase (~12.3–17.9%) while no differences were observed for the wall contact phase across all groups. The fastest rotation after the intervention was found in the open turn (1.24 ± 0.10 s). It appears that the four-week intervention programme could facilitate learning of backstroke to breaststroke turning techniques, but was insufficient to allow classifying one as the most predominantly improved and sensitive to the training programme. The study results suggest that the preferred turn technique is not always the better and that age-group swimmers are able to optimize their turning performance through regular turning practice sessions.

Key words: Breaststroke to breaststroke, intervention, biomechanics, kinematic-temporal, Kinetic.

Introduction

The analysis of swimming performance requires multiple measures to produce a more comprehensive and accurate assessment through various integrated temporal, kinematic, kinetic, electromyographic and hydrodynamic variables. Such analyses can be used to make a permanent record of performance, monitor training progress, track changes in performance-related variables and identify athlete strengths and weaknesses (Mooney et al., 2016). Research into young swimmers' performance has been previously conducted for tracking performance (Morais et al., 2013; Zacca et al., 2020), longitudinal modelling (Barbosa et al., 2010; Zacca et al., 2020), interaction and linking performance (Barbosa et al., 2010), cluster analysis (Figueiredo et al., 2016), task constraints and coordination (Silva et al., 2019), strength training intervention and coordination (Silva et al., 2019), effects of detraining (Zacca et al., 2020) and active drag (Havriluk, 2006).

For young swimmer performance, technical and endurance training are the two major contributions affecting primary outcomes (Barbosa et al., 2010; Marinho et al., 2009). Training interventions for strengthening technical capability in complex skills, such as turning technique, provide a meaningful idea of the extent of skill development and motor learning. In general, the effects of practice conditions on motor learning was examined from the perspective of two experimental variables: skill level and task difficulty (Guadagnoli and Lee, 2004). Following the long-term athlete-development framework, it was observed that learning, consolidating and progressively refining swimming skills, such as swimming, turning, starting and underwater skills, should be primarily emphasised in specific technical practice from an early age (Arellano, 2010; Junggren, Elbæk and Stambulova, 2018).

The technical training has been separated into cyclic (swimming technique) and non-cyclic (starts and turns) training (Arellano, 2010). Different biomechanical variables have been selected to identify and evaluate swimming techniques, such as intracyclic velocity variations and index of coordination index (Figueiredo et al., 2016; Silva et al., 2019); stroke characteristics, including stroke length (SL) and stroke frequency (SF) [Barbosa et al., 2010; Silva et al., 2019); and stroke efficiency, including stroke index (SI), propelling efficiency and swimming velocity (Figueiredo et al., 2016; Ricardo Peterson et al., 2019). For the starts and turns, some studies have shown that starting techniques may improve if swimmers undergo a specific intervention programme (Galbraith, Scurr and Hencken, 2008; Blanksby, Nicholson and Elliott, 2002) and that swimmers could further improve non-preferred techniques through regular training.

In light of recent research on turning techniques, an optimising teaching-learning process delivered through a training programme should be addressed as a priority for age-group swimmers (Zacca et al., 2020; Silva et al., 2019). Despite this interest, no intervention studies have been found with young swimmers, especially in relation to variants of breaststroke to breaststroke turns (open, somersault, bucket and crossover turns).Therefore, the purpose of this study is to examine the biomechanical characteristics of the four different breaststroke to breaststroke turning techniques following a four-week contextual interference programme with age-group swimmers.

Materials and Methods

Subjects

Twenty young swimmers belonging to the same swimming club were assessed after written informed consent was obtained from them and their guardians. The group included 10 boys and 10 girls. The boys' characteristics were as follows: 12.50 ± 0.53 years old, 159.05 ± 13.45 cm tall, with 48.74 ± 12.46 kg of body mass, 14.89 ± 5.18% kg of body fat, and a best performance of 174.33 ± 6.12 s in the 200 m short-course individual medley, which represents 71.6 ± 4.6 % of the world junior record. The girls' characteristics were as follows: 11.60 ± 0.52 years old, 151.75 ± 7.65 cm tall, with 46.73 ± 10.89 kg of body mass, 21.9 ± 7.1 % of body fat, and a best performance of 189.13 ± 9.12 s in the 200-m short-course individual medley, which represents 68.2 ± 8.2% of the world junior record. Both genders belonged to Tanner stages 2–4, according to the self-reported assessment at the beginning of the research. The study was approved by the local university ethics committee (code nº CEFADE 08.2014) in accordance with the Declaration of Helsinki.

Training protocol

Prior to the experiments, swimmers answered a questionnaire about their backstroke to breaststroke transition techniques preferences, with 16 selecting the *open* technique and only two the *somersault*. Then, they were submitted to a 2 h theoretical–practical lesson to instruct how to correctly perform each backstroke to breaststroke transition technique. This is especially important since learning from an expert can provide valuable information and help developing decision-making abilities while improving individuals' perceptual skills (Baker, Cote and Abernethy, 2003). During each lesson, coaches provided video images and continuous verbal descriptive and prescriptive feedbacks to correct swimmers' major technical errors.

Age-group swimmers underwent four weeks of 16 systematically contextual interference training programmes of 40 min each, following blocked, serial and random practice. Swimmers followed a block training plan schedule from the first to fourth sessions (each session focused on a different turning technique). The first serial training plan was run during the fifth to eighth scheduled training plans (the sequence of open, somersault, bucket and crossover turns was repeated twice for each turning technique: 4 x 10 min). The order of the second serial training plan was counterbalanced with two "laps" of 2 x (4 x 5 min) across all turning techniques from the ninth to twelve trial sessions. A random type training plan schedule with an equal number of trials was run during the thirteenth to sixteenth trial training sessions.

Testing procedures

At the beginning, all age-group swimmers completed a two-hour theoretical-practical lesson to instruct, demonstrate and facilitate acquisition of the four breaststroke to breaststroke turning techniques in terms of correct perception, decision-making and movement execution for each turning technique. Audio-visual explanations based on video images were used to demonstrate the appropriate technique concerning each key element, namely, approaching the wall, rotation, push-off, glide and stroke resumption. During pre- and post-intervention testing sessions, after a typical warm up, swimmers performed, in a randomised manner, 12 maximal 15 m repetitions of swimming 7.5 m to the wall, turning and gliding, and resuming swimming until the 7.5 mark. Each swimmer performed three repetitions for each breaststroke to breaststroke turning technique, with a three-minute rest between trials. The average values of the selected variables of the three trials for each turning technique were calculated for posterior analysis.

Data collection

To record swimmers' performance, a twenty-three-camera motion capture (MoCap) setup was used to track 51 reflective markers with 12 aerial and 11 underwater cameras (Oqus3 and 4 series, Qualisys, Gothenburg, Sweden) (Figure 1. upper left panel). The cameras were positioned to cover a cubic volume of approximately 30 m^3 (10 m long × 2 m wide × 1.5 m deep) of water, where the orthogonal axes were defined as X, Y and Z for horizontal, medio-lateral, and vertical (Z = 0 defines water surface) movements, respectively. Calibration of the 3D motion capture system was performed following manufacturer guidelines using a twin-system setup in three consecutive steps: processing of the underwater, the above-water and the merging together of an acquisition. Regarding complex movements, particularly during the rotation phase, missing information on the automatically selected tracking markers represented up to ~ 30–135 frames (at most, 2.9–12.2% of the trial duration). After reducing the amount of missing information on selected markers, Qualisys Track Manager Software was used to fill the missing gap using a built-in spline interpolation.

Kinetic assessment was conducted using two underwater tri-axial force plates sampling at a frequency of 200 Hz. The underwater structure included two independent force plates currenting a flat rectangular surface that were vertically fixed on a turning pool wall on a specially built support [18] (Figure1. lower left panel). The sensitivity of the two force plates was 0.5 N, and an error margin < 5% was considered acceptable for accurate and reliable measurements. To convert digital data through an analogue, all strain outputs were converted to strain gauge input modules (NI 9237, NI Corporation, Austin, Texas, USA) connected to a chassis (Compact DAQ USB-9172 and Ethernet-9188; NI Corporation, Austin, Texas, USA) (Tor, Pease and Ball, 2015). Moreover, to allow kinematic-temporal and kinetic synchronisation, a custom-built trigger box was used to manually generate starting commands based on a 5V TTL signal, as in Figure 1. lower right panel (de Jesus et al., 2019).

Data processing

Qualisys Track Manager (Qualisys, Gothenburg, Sweden) software was used to acquire the kinematic-temporal data on 15 m turn time (7.5 m in + 7.5 m out). Each reflective track marker was identified using the respective anatomical reference label, and the referential system was set by using four points of the reflective marker on the wall, corresponding to a 7.5 m distance from the wall (Figure 1. upper right panel). To optimize the digital filter cut-off frequency of all kinematic-temporal data, a residual analysis based on the fast Fourier transform was performed using the software Acknowledge v. 3.9.0 (Acknowledge, BIOPACiopac® Systems, Inc., Santa Barbara, California, USA). A digital filter with a cut-off frequency of 6 Hz was used to low-pass filter the kinematic–temporal data.

Kinetic data processing was divided into two consecutive processes: (i) data acquisition of the force and moment plot and recording of the strain readings of each triaxial force plate was achieved using custom LabView 2013 (SP1, NI™, USA) software, and (ii) kinetic variables were acquired using custom-designed routine software created in Matlab (MathWorks Inc., USA). The routine comprised the following steps: (1) offset correction; (2) filtering (using a fourth-order zero-phase digital Butterworth filter with a 10 Hz cut-off frequency); (3) verification of the selected kinetic variables, namely, force peak (i.e., maximum value of the X, Y, Z force), wall contact time (WCT) and horizontal impulse for both wall support and pushing phases; and (4) analysing an average of three trials for each turning technique analysed.

Given that our findings were derived without separating the bow wave from swimmer contact forces, the results from such analyses should be treated with considerable caution, particularly the verification and detection of the real contact force instant. Firstly, an image-based kinematics approach was used by manually generating starting commands and, afterwards, the detection of force profiles was conducted case by case by mainly considering time offset between the instant of contact and the trigger event, as well as swimmers' feet placement at contact. Then, verification of the selected kinetic variables reported as dominant push-off force (DPO) to identify the characteristics of the peak force contribution of the X, Y and Z components in each turning technique.

Data analysis

Backstroke to breaststroke turning techniques were divided into five phases: (1) approach - from hand's entry 7.5 m from the wall until touching the wall; (2) rotation - from the first hand's wall contact until the swimmer's feet touch the wall; (3) wall contact - from first wall contact until the feet leave the wall; (4) gliding - divided into three sub-phases, namely: (i) first gliding, (ii) transition phase and (iii) second gliding (from the feet leaving the wall until the arms are extended at the side of the trunk) and (5) stroke resumption, from the arms and legs recovery action until the vertex of the head passes the 7.5-m marker from the wall. Kinematic-temporal and kinetic selected variables are presented in Table 1.

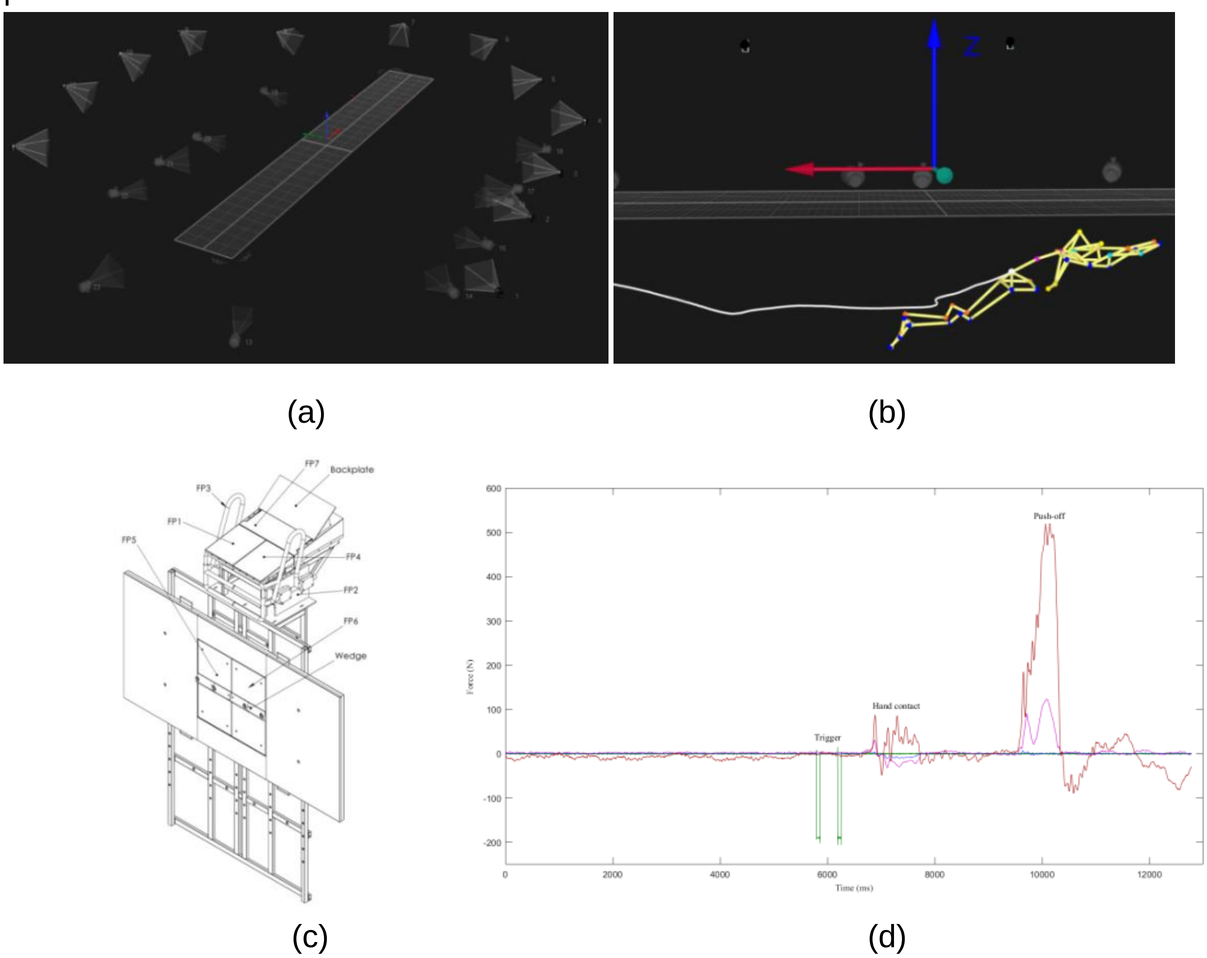

Figure1. Kinematic-temporal and kinetic data set up and data processing: (a) experimental cameras positioning, calibration volume and the origin of the tri-axial reference frame; (b) kinematic-temporal traces of the sacrum; (c) two tri-axial force plates set up; (d) force-time curve of two tri-axial force plate profiles.

Statistical analysis

All kinematic-temporal and kinetic variables were checked for normality with the Shapiro-Wilk test. Group means, mean standard errors and 95% confidence intervals were computed. A paired t-test was used to analyse differences between pre- and post-intervention of mean time contribution for each sub-phase in each turning technique. Sphericity was verified using Bartlett's test prior to running ANOVA. A one-way ANOVA was conducted to determine whether there was a statistically significant difference in the biomechanical characteristics of the four different backstroke to breaststroke turning techniques over the four-week programme, which included systematically increasing contextual interference intervention in age-group swimmers. Provided that a significant effect was found, post hoc pairwise comparisons using Turkey's HSD were conducted. Omega squared (ω^2) was selected as the variance effect size index to provide an unbiased estimate of effect size (Levine and Hullett, 2002; Lauer et al., 2016). The effect size was small if $\omega^2 \leq 0.06$, moderate if $0.07 < \omega^2 \leq 0.14$ and large if s 0.14. The alpha significance level was established at 0.05.

Results

Mean time and percentage contributions for each sub-phase of the breaststroke to breaststroke turn variants between pre- and post-intervention are presented in Table 1. A comparison of mean time contributions revealed significant differences between pre- and post-intervention in approach (d = 0.79–1.00; $p < 0.01$), rotation (d= 0.73–1.34; $p< 0.01$), turn out phase (d = 0.01–0.14; $p < 0.05$) and 15 m turning time (d = 0.50–0.60; $p < 0.01$), while no significant differences were observed in the wall contact phase across all turning techniques. The approach phase showed the highest contribution compare to the other phase after the four-week intervention programme across all turning techniques (approach, rotation, wall contact and turn-out: 45, 8, 3 and 44%, respectively). There was significant improvement in the 15 m turning time over the intervention period ($p < 0.01$), with the highest improvement in somersault turn (5.3 %, 0.91 s) and the fastest turn identified as the bucket turn (16.27 ± 1.60 s) (Table 2).

Table1. Kinematic-temporal and kinetic variables selected in each turning techniques, respective units and definition.

Variables	Definition
7.5 m time in (s)	Time between swimmers' vertex reached 7.5 m correspondence to the hand touching the wall at an origin of referential system.
5.0 m time in (s)	Time between swimmers' vertex reached 5.0 m correspondence to the hand touching the wall at an origin of referential system.
2.5m time in (s)	Time between swimmers' vertex reached 2.5 m correspondence to the hand touching the wall at an origin of referential system.
5^{th} SL (m)	The fifth upper limbs cycle length that was obtained by the horizontal displacement of the one upper limbs cycle prior to the wall.
4^{th} SL (m)	The fourth upper limbs cycle length that was obtained by the horizontal displacement of the one upper limbs cycle prior to the wall.
3^{rd} SL (m)	The third upper limbs cycle length that was obtained by the horizontal displacement of the one upper limbs cycle prior to the wall.
2^{nd} SL (m)	The second upper limbs cycle length that was obtained by the horizontal displacement of the one upper limbs cycle prior to the wall.
Last upper limbs -wall distance (m)	Middle finger to wall distance at the last upper limbs cycle.
Average SL during turn-in (m)	The mean of the last five upper limbs cycle length that was obtained by the horizontal displacement of the one upper limbs cycle.
5^{th} SR (cycles · min^{-1})	The fifth upper limbs cycles dividing by the time duration of the fifth stroke prior to the wall.
4^{th} SR (cycles · min^{-1})	The fourth upper limbs cycles dividing by the time duration of the fourth stroke prior to the wall.
3^{rd} SR (cycles · min^{-1})	The third upper limbs cycles dividing by the time duration of the third stroke prior to the wall.
2^{nd} SR (cycles · min^{-1})	The second upper limbs cycles dividing by the time duration of the second stroke prior to the wall.
Last stroke SR(cycles · min^{-1})	The last upper limbs cycles dividing by the time duration of the first stroke prior to the wall.
Average SR (cycles · min^{-1})	The average of the stroke rate of the last five upper limbs cycles to the wall.
Touching depth (m)	Depth at the hand at touching the wall.
Hand contact time (s)	Time at hand contact to the wall.
Rotation time (s)	Time between hand contacts to feet contact to the wall.
Hand peak X force (N)	The highest force applied while hand pushing to the left / right on the force plate during hand contact.
Hand peak Y force (N)	The highest force applied while hand pushing up or down on the force plate during hand contact.
Hand peak Z force (N)	The highest force applied perpendicular to the force plate during hand contact.
Hand contact impulse (Z) (Ns.)	The area under the perpendicular Z force-time curve during hand contact.
Tuck index (%)	Distance of right hip from the wall at the beginning of push-off, divided by swimmer's leg length.

Table1. Kinematic-temporal and kinetic variables selected in each turning techniques, respective units and definition (continued).

Variables	Definition
Foot plant index (%)	Depth of the foot plant on the wall at the beginning of push-off, divided by swimmer's leg length.
Total wall contact time (s)	Total feet contact time to the wall.
Push-off time (s)	Time of feet with wall while hips move forward until the swimmer's feet had left the wall.
Feet peak X force (N)	The highest force applied while feet pushing to the left or right to the swimmer's feet had left the wall.
Feet peak Y force (N)	The highest force applied while feet pushing up or down during to the swimmer's feet had left the wall.
Feet peak Z force (N)	The highest force applied while feet horizontal pushing to the swimmer's feet had left the wall.
Feet contact impulse (Z) (Ns.)	The area under the Z force-time curve during the foot push-off to the swimmer's feet had left the wall.
Push-off velocity ($m \cdot s^{-1}$)	Resultant velocity of swimmer's sacrum at the swimmer's feet had left the wall.
First gliding distance (m)	Distance of sacrum travel from the swimmer's feet had left the wall to the first frame of the transition phase.
First gliding time (s)	Time of swimmer's sacrum travel from the beginning of feet had left the wall to the first frame of transition.
First gliding depth (m)	Average of swimmer's sacrum depth during the gliding phase.
Transition distance (m)	Distance of swimmer's sacrum travel from the initial separation of the hands or starting dolphin kick until upper limbs extended at the sides of the body.
Transition time (s)	Time of swimmer's sacrum travel from the initial of hands separate or starting dolphin kick until the arms fully extended at sides of the body.
Transition gliding depth(m)	Average of swimmer's sacrum depth during transition phase.
Second gliding distance (m)	Distance of swimmer's sacrum travel from the first frame of the arms fully extended at sides of the body to the instant in which swimmer begins to move hands from side of the body up.
Second gliding time (s)	Time of swimmer's sacrum travel from the first frame of the arms fully extended at the sides of the body to an instant which swimmer begins to move hands from side of the body up.
Second gliding depth (m)	An average of swimmer's sacrum depth during the second gliding phase.
Breakout distance (m)	Distance at which the swimmer's head breaks the surface for the first time.
Breakout time (s)	Time at which the swimmer's head breaks the surface for the first time.
Time out (s)	Time from the swimmer's had left the wall to the swimmer's head reached 7.5 m.
15 m turning time (s)	The turn time performance including 7.5 m time in and 7.5 m time out.

The average 7.5 m, 5.0 m and 2.5 m time in for all turning techniques were reduced ($p < 0.01$) and average stroke length, the last SL and the last stroke hand-wall distance were decreased over the intervention period ($p < 0.01$). The stroke rate (SR) remained relatively similar from pre - to post-intervention across turning techniques (Figure. 2). Pre-intervention variations in the last stroke hand-wall distance correlated with post-intervention differences. ($F = 4.26$, $p < 0.01$, $\omega^2 = 0.04$, small effect and $F = 3.03$, $p = 0.03$, $\omega^2 = 0.03$, small effect, respectively). The longer last stroke hand-wall distance was observed in the somersault at both the pre-intervention and post-intervention (0.78 ± 0.26 vs 0.56 ± 0.24 m) (Table 2).

When differences between the rotation phase at pre- and post-intervention were examined, there were difference in touching depth, hand peak X, Y and Z forces and rotation time ($p < 0.01$) across all turning techniques. ANOVA indicated that turning techniques at post-intervention were difference in touching depth ($F = 70.76$, $p < 0.01$, $\omega^2 = 0.47$, large), hand contact time ($F = 18.10$, $p < 0.01$, $\omega^2 = 0.18$, large), hand peak X force ($F = 3.82$, $p < 0.01$, $\omega^2 = 0.04$, small), hand peak Y force ($F = 12.45$, $p < 0.01$, $\omega^2 = 0.13$, moderate) and hand peak Z forces ($F = 9.31$, $p < 0.01$, $\omega^2 = 0.10$, moderate). The significant pairwise comparisons of each rotation variable are displayed in Table 3.

The kinematic variables that could have potentially significant effects on push-off velocity yielded mixed results. The tuck index and foot plant index were lower after the intervention period across all turning techniques ($p < 0.01$). Total wall contact time (s) was higher after the intervention period for crossover turns ($p < 0.05$), whereas push-off times were higher for somersault and crossover turns ($p < 0.01$), respectively. There were differences in the foot plant index ($F = 11.73$, $p < 0.01$, $\omega^2 = 0.12$, moderate), total wall contact time ($F = 4.76$, $p < 0.01$, $\omega^2 = 0.05$, small), and push-off time ($F = 4.71$, $p < 0.01$, $\omega^2 = 0.05$, small) at post-intervention period.

Table 2. Mean time and percentage time contribution for each sub-phase of the backstroke to breaststroke turns between pre intervention and post intervention.

Sub- phase	Turns	Time (s)					Percentage Contribution (%)	
		PRE	POST	p	Difference [95%CI];%Δ	Effect size (d)	PRE	POST
Approach phase	Open	8.03 + 0.79	7.42 + 0.63	0.01<	-0.61[0.53-0.70]; -7.60%	0.85	46	45
	Somersault	7.98 + 0.70	7.35 + 0.55	0.01<	-0.63[0.54-0.72]; -7.89%	1.00	46	45
	Bucket	7.87 + 0.78	7.30 + 0.65	0.01<	-0.57[0.47-0.67]; -7.24%	0.79	46	45
	Crossover	8.09 + 0.87	7.45 + 0.70	0.01<	-0.64[0.53-0.75]; -7.91%	0.81	46	45
Rotation phase	Open	1.51 + 0.22	1.24 + 0.18	0.01<	-0.27[0.24-0.30]; -17.88%	1.34	9	8
	Somersault	1.46 + 0.24	1.28 + 0.24	0.01<	-0.18[0.15-0.22]; -12.33%	0.75	9	8
	Bucket	1.53 + 0.29	1.31 + 0.27	0.01<	-0.22[0.17-0.25]; -14.37%	0.79	9	8
	Crossover	1.52 + 0.28	1.33 + 0.24	0.01<	-0.19[0.16-0.23]; -12.50%	0.73	9	8
Wall contact phase	Open	0.58 + 0.17	0.57 + 0.19	0.57	-0.01[-0.02-0.30]; -1.72%	0.06	3	3
	Somersault	0.55 + 0.10	0.54 + 0.12	0.17	-0.01[-0.01-0.04]; -1.72%	0.09	3	3
	Bucket	0.53 + 0.13	0.53 + 0.12	0.63	-0.00[-0.03-0.02]; 0.00%	0.00	3	3
	Crossover	0.60 + 0.18	0.63 + 0.18	0.07	-0.03[-0.06-0.01]; 5.00%	-0.17	3	3
Turn out phase	Open	7.34 + 0.88	7.22 + 0.87	0.05<	-0.12[0.01-0.08]; -1.50%	0.14	42	44
	Somersault	7.33 + 0.96	7.09 + 0.97	0.05<	-0.24[0.01-0.04]; -3.27%	0.25	42	44
	Bucket	7.18 + 0.86	7.07 + 0.84	0.05<	-0.11[0.01-0.09]; -1.53%	0.13	42	44
	Crossover	7.13 + 0.89	7.13 + 0.89	0.05<	-0.00[0.02-0.02]; 0.00%	0.01	42	44
15 m turning time (s)	Open	17.41 + 1.62	16.53 + 1.53	0.01<	-0.88[0.85-1.03]; -5.05%	0.56	100	100
	Somersault	17.32 + 1.57	16.41 + 1.47	0.01<	-0.91[0.79-1.01]; -5.25%	0.60	100	100
	Bucket	17.09 + 1.71	16.27 + 1.60	0.01<	-0.82[0.71-0.94]; -4.80%	0.50	100	100
	Crossover	17.53 + 1.70	16.67 + 1.52	0.01<	-0.86[0.76-0.97]; -4.91%	0.53	100	100

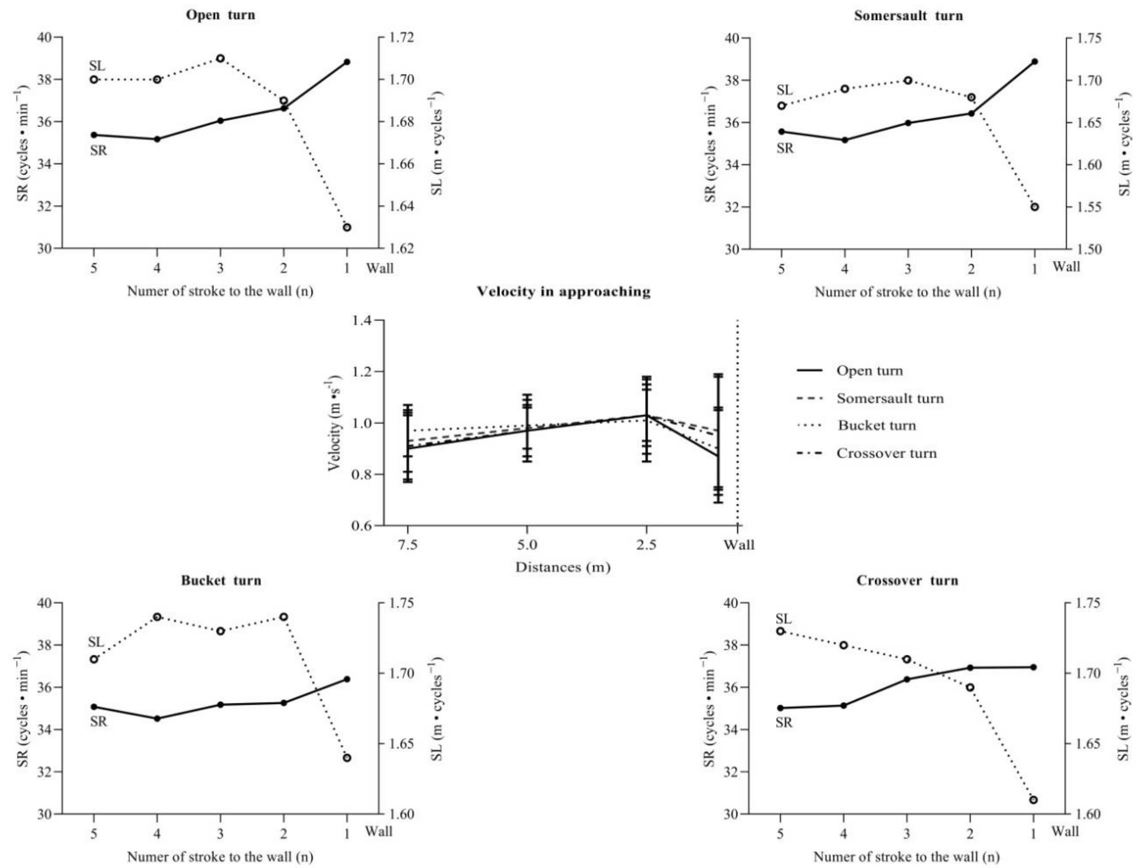

Figure 2. Swimming velocity, stroke rate and stroke length of the four difference backstroke to breaststroke turns during approach phase after the four-week of systematic contextual interference training program.

Analyzing the kinetic variables between pre- and post-intervention revealed that there were different peak horizontal Z forces in the open turn ($p < 0.01$) and somersault turn ($p < 0.05$), while the highest peak horizontal Z force was found in the crossover turn ($p = 0.56$). The peak vertical forces (Y) were lower from the pre-intervention in open and somersault ($p < 0.01$) but higher in bucket turns ($p < 0.05$). However, there was no difference in medial-lateral peak force (X) across all turns. Besides, there was no significant difference in foot contact impulse across all turning techniques. The significant main effects among each turn were observed in vertical peak force (Y) ($F = 9.01$, $p < 0.01$, $\omega^2 = 0.09$, small) and horizontal peak force (Z) ($F = 5.66$, $p < 0.01$, $\omega^2 = 0.06$, small). The pairwise comparisons of each kinematic and kinetic variable are displayed in Table 4.

Table 3. Mean ± SD and ANOVA results for turning differences on approach phase variables.

Variables	Descriptive				Anova		
	Open	Somersault	Bucket	Crossover	F-ratio	*p*	ω^2
	Mean ± 1SD	Mean ± 1SD	Mean ± 1SD	Mean ± 1SD	(3,232)		
Pre- intervention							
7.5 m time in (s)	8.03 ± 0.79	7.98 ± 0.70	7.87 ± 0.78	8.09 ± 0.87	0.74	0.53	-0.00
5 m time in (s)	5.88 ± 0.83	5.84 ± 0.74	5.73 ± 0.86	5.94 ± 0.92	0.56	0.64	-0.00
2.5 m time in (s)	3.12 ± 0.64	3.10 ± 0.56	3.11 ± 0.62	3.16 ± 0.67	0.11	0.96	-0.01
5th SL (m)	1.81 ± 0.25	1.81 ± 0.21	1.85 ± 0.26	1.84 ± 0.24	0.45	0.72	-0.00
4th SL (m)	1.82 ± 0.23	1.82 ± 0.22	1.90 ± 0.25	1.85 ± 0.23	1.22	0.30	0.01
3rd SL (m)	1.78 ± 0.24	1.76 ± 0.21	1.81 ± 0.26	1.78 ± 0.23	0.29	0.83	-0.01
2nd SL (m)	1.76 ± 0.26	1.75 ± 0.20	1.81 ± 0.26	1.76 ± 0.26	0.65	0.58	-0.00
Last stroke SL (m)	1.78 ± 0.31	1.71 ± 0.29	1.81 ± 0.34	1.79 ± 0.36	0.98	0.40	-0.00
Average SL (m)	1.79 ± 0.23	1.77 ± 0.20	1.84 ± 0.23	1.80 ± 0.23	0.80	0.49	-0.00
5th SR (cycles · min^{-1})	34.86 ± 6.17	35.47 ± 5.81	33.89 ± 6.47	34.68 ± 6.21	0.61	0.61	-0.00
4th SR (cycles · min^{-1})	35.05 ± 6.04	35.12 ± 5.95	32.70 ± 5.87	34.76 ± 6.31	1.76	0.16	0.01
3rd SR (cycles · min^{-1})	34.97 ± 6.35	34.87 ± 5.72	34.94 ± 6.64	35.13 ± 6.75	0.02	0.99	-0.01
2nd SR (cycles · min^{-1})	35.56 ± 7.10	35.01 ± 5.37	34.40 ± 7.47	35.65 ± 7.30	0.35	0.79	-0.01
Last SR (cycles · min^{-1})	36.41 ± 8.43	37.46 ± 7.41	34.56 ± 9.05	36.39 ± 8.65	0.99	0.40	-0.00
Average SR (cycles · min^{-1})	35.37 ± 6.34	35.59 ± 5.47	34.15 ± 6.21	35.32 ± 6.43	0.54	0.66	-0.00
Last stroke H–W distance(m)	0.63 ± 0.29^{s}	0.78 ± 0.26^{o}	0.76 ± 0.25	0.66 ± 0.28	4.26	0.01	0.04
Post- intervention							
7.5 m time in (s)	7.42 ± 0.63**	7.35 ± 0.55**	7.30 ± 0.65**	7.45 ± 0.70**	0.61	0.61	-0.00
5 m time in (s)	5.27± 0.56**	5.21 ± 0.48**	5.16± 0.61**	5.29 ± 0.62**	0.61	0.61	-0.00
2.5 m time in (s)	2.50 ± 0.36**	2.48 ± 0.29**	2.54 ± 0.37**	2.52 ± 0.34**	0.37	0.77	-0.01
5th SL (m)	1.68 ± 0.23**	1.66 ± 0.19**	1.70 ± 0.23**	1.71 ± 0.22**	0.47	0.70	-0.00
4th SL (m)	1.69 ± 0.21**	1.68 ± 0.21**	1.74 ± 0.23**	1.71 ± 0.21**	0.99	0.40	-0.00
3rd SL (m)	1.68 ± 0.23**	1.67 ± 0.21**	1.71 ± 0.25**	1.68 ± 0.22**	0.28	0.84	-0.01
2nd SL (m)	1.67 ± 0.25**	1.66 ± 0.20**	1.72 ± 0.25**	1.67 ± 0.25**	0.66	0.58	-0.00
Last stroke SL (m)	1.61 ± 0.28**	1.53 ± 0.27**	1.62 ± 0.31**	1.58 ± 0.34**	1.18	0.32	0.00
Average SL (m)	1.67 ± 0.20**	1.63 ± 0.17**	1.70 ± 0.22**	1.67 ± 0.20**	1.05	0.37	0.00
5th SR (cycles · min^{-1})	35.37 ± 7.17	35.57 ± 5.65	35.08 ± 6.62	35.02 ± 6.72	0.06	0.98	-0.01
4th SR (cycles · min^{-1})	35.17 ± 6.41	35.17 ± 5.82	34.52 ± 6.50	35.14 ± 6.99	0.11	0.96	-0.01
3rd SR (cycles · min^{-1})	36.05 ± 7.12	35.98 ± 6.18	35.18 ± 6.97	36.38 ± 7.61	0.25	0.86	-0.01
2nd SR (cycles · min^{-1})	36.63 ± 7.85	36.43 ± 6.28	35.26 ± 7.99	36.93 ± 8.35	0.43	0.73	-0.01
Last SR (cycles · min^{-1})	36.83 ± 7.98	38.89 ± 8.24	36.39 ± 8.55	36.95 ± 8.09	0.95	0.42	-0.00
Average SR (cycles · min^{-1})	36.01 ± 6.79	36.41 ± 5.76	35.23 ± 6.89	36.08 ± 6.87	0.26	0.85	-0.01
Last stroke H–W distance(m)	0.44 ± 0.25^{s**}	0.56 ± 0.24^{o**}	0.52 ± 0.24**	0.46 ± 0.27**	3.03	0.03	0.03

o Significantly different from Open turn ($p < 0.05$).
s Significantly different from Somersault turn ($p < 0.05$).
b Significantly different from Bucket turn ($p < 0.05$).
c Significantly different from Crossover turn ($p < 0.05$).
* Significantly different from Pre-intervention ($p < 0.05$).
** Significantly different from Pre-intervention ($p < 0.01$).

The kinematic variables that could have potentially significant effects on push-off velocity yielded mixed results. The paired samples *t*-test indicated that the tuck index and foot plant index were significantly lower after the intervention period across all turning techniques ($p < 0.01$). Total wall contact time (s) was significantly higher after the intervention period for crossover turns ($p < 0.05$), whereas push-off times were significantly higher for somersault and crossover turns ($p < 0.01$), respectively. ANOVA indicated that turning techniques at post-intervention were differences in the foot plant index ($F = 11.73$, $p < 0.01$, $\omega^2 = 0.12$, moderate), total wall contact time ($F = 4.76$, $p < 0.01$, $\omega^2 = 0.05$, small) and push-off time ($F = 4.71$, $p < 0.01$, $\omega^2 = 0.05$, small).

Analyzing the kinetic variables between pre- and post-intervention revealed that there were significantly different peak horizontal Z forces in the open turn ($p < 0.01$) and somersault turn ($p < 0.05$), while the highest peak horizontal Z force was found in the crossover turn ($p = 0.56$). The peak vertical forces (Y) were significant in open, somersault ($p < 0.01$), and bucket turns ($p < 0.05$), whereas no difference in medial-lateral peak force (X) was found across all turns. However, there was no significant difference in foot contact impulse across all turning techniques. ANOVA also indicated that the significant main effects among each turn were for vertical peak force (Y) ($F = 9.01$, $p < 0.01$, $\omega^2 = 0.09$, small) and horizontal peak force (Z) ($F = 5.66$, $p < 0.01$, $\omega^2 = 0.06$, small). Significant pairwise comparisons of each kinematic and kinetic variable are displayed in Table 5.

Table 4. Mean ± SD and ANOVA results for turning differences on rotation phase variables.

Variables	**Descriptive**				**Anova**		
	Open Mean ± 1SD	Somersault Mean ± 1SD	Bucket Mean ± 1SD	Crossover Mean ± 1SD	F-ratio (3,232)	*p*	ω^2
Pre- intervention							
Touching depth (m)	0.24 ± 0.01^{s}	0.43 ± 0.01^{o,b,c}	0.24 ± 0.01^{s}	0.20 ± 0.01^{s}	64.15	0.01	0.45
Hand contact time (s)	0.47 ± 0.02^{b,c}	0.48 ± 0.02^{b,c}	0.59 ± 0.02^{o,s,c}	0.35 ± 0.02^{o,s,b}	17.97	0.01	0.18
Rotation time (s)	1.51 ± 0.17	1.46 ± 0.23	1.52 ± 0.29	1.52 ± 0.27	0.96	0.41	-0.00
Hand peak X force (N)	1.90 ± 0.52	1.98 ± 0.50	2.01 ± 0.58	1.84 ± 0.42	1.23	0.30	0.01
Hand peak Y force (N)	6.24 ± 3.12^{b}	6.76 ± 3.17^{b}	10.25 ± 6.94^{o,s,c}	5.63 ± 3.67^{b}	11.75	0.01	0.12
Hand peak Z force (N)	15.03 ± 6.74^{s}	26.58 ± 17.11^{o,c}	22.04 ± 13.51^{c}	13.29 ± 6.89^{s,b}	9.14	0.01	0.09
Hand contact impulse (Ns.)	7.26 ± 4.83^{s,b}	13.26 ± 8.91^{o,c}	13.01 ± 8.83^{o,c}	4.67 ± 2.80^{s,b}	14.09	0.01	0.14
Post- intervention							
Touching depth (m)	0.17 ± 0.09^{s**}	0.35 ± 0.12^{o,b,c**}	0.16 ± 0.09^{b**}	0.13 ± 0.06^{s**}	70.86	0.01	0.47
Hand contact time (s)	0.48 ± 0.21^{b,c}	0.48 ± 0.16^{b,c}	0.59 ± 0.15^{o,s,c}	0.35 ± 0.12^{o,s,b}	18.10	0.01	0.18
Rotation time (s)	1.24 ± 0.18**	1.28 ± 0.24**	1.31 ± 0.27**	1.33 ± 0.24**	1.69	0.17	0.01
Hand peak X force (N)	1.56 ± 0.33**	1.62 ± 0.23^{c**}	1.64 ± 0.22^{c**}	1.49 ± 0.22^{s,b**}	3.82	0.01	0.04
Hand peak Y force (N)	5.54 ± 2.96^{b**}	6.07 ± 2.82^{b**}	9.50 ± 6.81^{o,s,c**}	4.92 ± 3.47^{b**}	12.45	0.01	0.13
Hand peak Z force (N)	15.81 ± 6.53^{s**}	27.42 ± 16.81^{o,c**}	23.10 ± 13.96^{c**}	14.16 ± 7.11^{s,b**}	9.31	0.01	0.10
Hand contact impulse (Ns.)	7.39 ± 4.13^{s,b}	12.99 ± 12.12^{o,c}	13.32 ± 8.29^{o,c}	4.96 ± 3.13^{s,b}	16.56	0.01	0.17

^{o,s,b} and ^{c}: significantly different from open, somersault, bucket and crossover turn;
* significant different from Pre-intervention ($p < 0.05$);
** significant different from Pre-intervention ($p < 0.01$).

Turning to the turn-out phase, the final push-off velocities significantly improved after the intervention period across all turning techniques ($p < 0.01$). However, there were no significant main effects between each turning technique after the intervention period ($F = 2.26$, $p < 0.08$, $\omega^2 = 0.02$, small). Interestingly, there were significant differences in all variables between pre-intervention and post-intervention ($p < 0.01$). A significant main effect of turning techniques was observed, mainly on gliding depth (first gliding depth: $F = 48.91$, $p < 0.01$, $\omega^2 = 0.38$, large; transition gliding depth: $F = 26.15$, $p < 0.01$, $\omega^2 = 0.24$, large; second gliding depth: $F = 12.32$, $p < 0.01$, $\omega^2 = 0.13$, moderate). In comparison to the other three turns, the somersault turn had the greatest gliding depth during the gliding period. The significant pairwise comparisons of each gliding depth are displayed in Table 6.

Table 5. Mean ± SD and ANOVA results for turning differences on wall contact phase variables.

Variables	Descriptive				Anova		
	Open Mean ± 1SD	Somersault Mean ± 1SD	Bucket Mean ± 1SD	Crossover Mean ± 1SD	F-ratio (3,232)	*p*	ω^2
Pre- intervention							
Tuck index	0.80 ± 0.13	0.83 ± 0.14	0.81 ± 0.10	0.80 ± 0.15	0.75	0.53	-0.00
Foot plant index	- 0.60 ± 0.19 ^{s,c}	-0.69 ± 0.17 ^{o,b,c}	-0.56 ± 0.18 ^{s}	-0.49 ± 0.16 ^{o,s}	12.51	0.01	0.13
Total wall contact time (s)	0.58 ± 0.71	0.55 ± 0.10	0.53 ± 0.13	0.60 ± 0.17	2.40	0.07	0.02
Push-off time (s)	0.40 ± 0.12	0.38 ± 0.08	0.36 ± 0.09	0.41 ± 0.12	2.53	0.06	0.02
Feet peak X force (N)	21.79 ± 15.97^{s,b,c}	12.69 ± 5.67^{o}	14.00 ± 8.00^{o,c}	8.12 ± 3.41^{o,b}	20.86	0.01	0.20
Feet peak Y force (N)	64.80 ± 36.06^{s}	39.29 ± 21.83^{o,b,c}	57.74 ± 26.09^{s}	53.58 ± 29.15^{s}	8.37	0.01	0.09
Feet peak Z force (N)	149.46 ± 75.74^{b}	118.54 ± 52.36^{b}	186.12 ± 111.21^{o,s,c}	142.04 ± 12.64^{b}	8.23	0.01	0.09
Feet contact impulse (Ns.)	64.80 ± 36.06	39.29 ± 21.83	52.29 ± 38.30	53.58 ± 29.15	5.99	0.01	0.06
Post- intervention							
Tuck index	0.71 ± 0.11**	0.75 ± 0.10**	0.74 ± 0.09**	0.72 ± 0.13**	1.67	0.17	0.01
Foot plant index	-0.48 ± 0.20^{s,c**}	-0.57 ± 0.18^{o,b,c**}	-0.44 ± 0.17^{s**}	-0.37 ± 0.17^{o,s**}	11.73	0.01	0.12
Total wall contact time (s)	0.57 ± 0.19	0.54 ± 0.12^{c}	0.53 ± 0.12^{c}	0.63 ± 0.18^{s,b*}	4.76	0.01	0.05
Push-off time (s)	0.40 ± 0.16	0.42 ± 0.09**	0.37 ± 0.08^{c}	0.46 ± 0.12^{b**}	4.71	0.01	0.05
Feet peak X force (N)	21.53 ± 15.89^{s,b,c}	12.57 ± 5.43^{o}	14.42 ± 8.58^{o,c}	7.92 ± 3.21^{o,b}	20.51	0.01	0.20
Feet peak Y force (N)	61.63 ± 36.66^{s**}	37.60 ± 20.63^{o,b**}	68.08 ± 43.23^{s*}	53.37 ± 27.87^{s}	9.01	0.01	0.09
Feet peak Z force (N)	145.91 ± 76.25^{b**}	133.72 ± 65.49^{b*}	190.02 ± 118.41^{o,s,c}	141.44 ± 12.80^{b}	5.66	0.01	0.06
Feet contact impulse (Ns.)	51.82 ± 29.97**	49.36 ± 33.76**	57.74 ± 26.09**	51.91 ± 32.28	0.63	0.26	0.01

^{o,s,b} and ^{c}: significantly different from open, somersault, bucket and crossover turn;
* significant different from Pre-intervention ($p < 0.05$);
** significant different from Pre-intervention ($p < 0.01$).

Table 6. Mean ± SD and ANOVA results for turning differences on gliding and stroke resumption phase variables.

Variables	Descriptive				Anova		
	Open Mean ± 1SD	Somersault Mean ± 1SD	Bucket Mean ± 1SD	Crossover Mean ± 1SD	F-ratio (3,232)	*p*	ω^2
Pre- intervention							
Push-off velocity ($m \cdot s^{-1}$)	1.77 ± 0.34	1.75 ± 0.36	1.78 ± 0.37	1.88 ± 0.37	1.40	0.24	0.01
First gliding distance (m)	2.15 ± 0.54	2.34 ± 0.69	2.23 ± 0.71	2.17 ± 0.64	1.13	0.34	0.01
First gliding time (s)	1.07 ± 0.31	1.22 ± 0.51	1.21 ± 0.43	1.09 ± 0.19	2.31	0.08	0.02
First gliding depth (m)	0.53 ± 0.13[s]	0.76 ± 0.14[o,b,c]	0.59 ± 0.15[s]	0.54 ± 0.16[s]	31.20	0.01	0.28
Transition distance (m)	0.97 ± 0.11	0.97 ± 0.20	1.00 ± 0.16	0.98 ± 0.18	0.39	0.76	-0.01
Transition time (s)	0.86 ± 0.12	0.83 ± 0.13	0.84 ± 0.15	0.83 ± 0.13	0.79	0.50	-0.00
Transition gliding depth (m)	0.52 ± 0.14[s]	0.76 ± 0.17[o,b,c]	0.58 ± 0.19[s]	0.55 ± 0.16[s]	27.97	0.01	0.26
Second gliding distance (m)	0.66 ± 0.21	0.73 ± 0.29	0.75 ± 0.28	0.75 ± 0.28	1.65	0.18	0.01
Second gliding time (s)	0.62 ± 0.20	0.63 ± 0.26	0.73 ± 0.32	0.69 ± 0.27	2.07	0.11	0.01
Second gliding depth (m)	0.67 ± 0.15[s]	0.82 ± 0.14[o,b,c]	0.68 ± 0.18[s]	0.67 ± 0.15[s]	13.23	0.01	0.14
Breakout distance (m)	5.60 ± 0.91	5.76 ± 1.11	5.69 ± 0.97	5.68 ± 1.05	0.28	0.84	-0.01
Breakout time (s)	4.68 ± 0.84	4.68 ± 0.78	4.56 ± 0.78	4.51 ± 0.75	0.73	0.54	-0.00
Time out (s)	7.34 ± 0.88	7.33 ± 0.96	7.18 ± 0.86	7.32 ± 0.90	0.38	0.77	-0.01
Post- intervention							
Push-off velocity ($m \cdot s^{-1}$)	2.02 ± 0.27**	1.96 ± 0.29**	2.00 ± 0.31**	2.11 ± 0.29**	2.26	0.08	0.02
First gliding distance (m)	2.23 ± 0.54**	2.52 ± 0.69**	2.41 ± 0.70**	2.35 ± 0.63**	1.05	0.37	0.00
First gliding time (s)	1.16 ± 0.31**	1.31 ± 0.51**	1.30 ± 0.44**	1.18 ± 0.19**	2.37	0.07	0.02
First gliding depth (m)	0.47 ± 0.09[s,b]**	0.70 ± 0.10[o,b,c]**	0.53 ± 0.14[o,s]**	0.48 ± 0.13[s]**	48.91	0.01	0.38
Transition distance (m)	1.07 ± 0.11**	1.06 ± 0.21**	1.09 ± 0.16**	1.07 ± 0.19**	0.34	0.80	-0.01
Transition time (s)	0.95 ± 0.12**	0.92 ± 0.13**	0.93 ± 0.14**	0.92 ± 0.14**	0.84	0.47	-0.00
Transition gliding depth (m)	0.61 ± 0.14[s]**	0.86 ± 0.17[o,b,c]**	0.68 ± 0.20[s]**	0.64 ± 0.17[s]**	26.15	0.01	0.24
Second gliding distance (m)	0.76 ± 0.22**	0.83 ± 0.30**	0.86 ± 0.28**	0.86 ± 0.30**	1.68	0.17	0.01
Second gliding time (s)	0.73 ± 0.20**	0.74 ± 0.27**	0.84 ± 0.32**	0.79 ± 0.27**	2.17	0.09	0.01
Second gliding depth (m)	0.60 ± 0.15[s]**	0.75 ± 0.14[o,b,c]**	0.62 ± 0.18[s]**	0.61 ± 0.16[s]**	12.32	0.01	0.13
Breakout distance (m)	5.83 ± 0.81**	6.01 ± 1.01**	5.93 ± 0.87**	5.92 ± 0.98**	0.39	0.76	-0.01
Breakout time (s)	4.75 ± 0.81**	4.76 ± 0.74**	4.63 ± 0.71**	4.58 ± 0.72**	0.78	0.50	-0.00
Time out (s)	7.30 ± 0.92**	7.26 ± 1.05**	7.12 ± 0.86**	7.25 ± 0.92**	0.33	0.80	-0.01

[o,s,b] and [c]: significantly different from open, somersault, bucket and crossover turn;

* significant different from Pre-intervention ($p < 0.05$);

** significant different from Pre-intervention ($p < 0.01$).

Discussion

There have been no previous studies comparing the biomechanical characteristics of the four different breaststroke to breaststroke turning techniques. The purpose of this study was to examine the biomechanical characteristics of the four different breaststroke to breaststroke turning techniques following a four-week contextual interference programme with age-group swimmers. Overall, the 15 m turning time for all turns was significantly improved over the intervention period (17.09–17.53s vs. 16.2–16.67s; $p < 0.01$), with the somersault turn showing the greatest improvement followed by the open turn, crossover turn and bucket turn (5.3, 5.1, 4.9 and 4.8%), respectively. Across all turning techniques, the percentages of time spent corresponding to the 15 m turning time performance were 46 vs. 45 % at the approach phase, 9 vs. 8 % at the rotation phase, 3 vs. 3 % at the wall contact phase, and 42 vs. 44 % at the turn-out phase.

The results from this study indicate that an intervention programme offering systematic increases in contextual interference facilitates learning of breaststroke to breaststroke turning techniques. This supports the view that specific practices adequate to the learner's skill level must be considered and addressed in regular training programmes to improve perceptual learning skills and increase technical efficacy (Porter and Magill, 2010). Curiously, this behaviour has also been observed for front crawl flip turn techniques (Pereira et al., 2015) and swimming starts after an intervention period (Galbraith et al., 2008). Furthermore, this result is consistent with Guadagnoli and Lee's observation that gradual increases in contextual interference could directly facilitate and enhance perceptual learning skills (Guadagnoli and Lee, 2004). However, the four-week intervention programme was not long enough to justify classifying any particular skill as the most predominantly improved and sensitive to the training programme. Thus, more longitudinal studies are required, particularly if the intervention period can be extended to better understand the influence and relationship among different biomechanical variables.

This observation is a crucial consideration, particularly as a consequence of indeterminate interactions between learners and the environment, which also contributes to the effectiveness of the improvement in turning technique. Most of the studies examining performance among different starting techniques have reported that swimmers performed their best starts using a technique that they preferred and had previous experience with (Pearson et al.,1998). However, by contrast, Tor et al. observed that swimmers' preferred starting techniques do not always lead to the fastest performance (Blanksby, Nicholson and Elliott, 2002). Our study contributed to the existing knowledge on intervention programs that can particularly impact not just non-preferred turning techniques in elite swimmers (Blanksby, Nicholson and Elliott, 2002), but also breaststroke to breaststroke turning techniques in young swimmers. Furthermore, motor skill training for novice or age-group swimmers should be organized based on the suitable practice environment in conjunction with a structured training program that can directly assist to enhance decision-making (Araújo, 2007) and adequately challenge skill-learning (Porter and Magill, 2010).

Nonetheless, no single biomechanical variables or specific relationship to a single turning phase proves totally satisfying in the case of track down performance and its determining variables that contribute to overall breaststroke to breaststroke turn performance. The main challenge remains the implementation and integration of biomechanical analysis with a systematically increasing contextual interference training program in obtaining the first insight into facilitating the teaching-learning process and determining the most relevant variable for each breaststroke to breaststroke turning performance. Consequently, the contribution of each turning phase, as well as key biomechanical characteristics that affect turning performance in each subsequent phase, must be clearly verified.

The approach time (7.5 m to the wall) was significantly reduced over the intervention period across all turns, indicating an overall effect of turn technique practice. These findings are in accordance with those reported by Nicol et al. (2019), who indicated that turn in time was the variable most strongly correlated to total turn time in freestyle. The literature is consistent in reporting that swimmers should maintain swimming speed (Webster et al., 2011) and momentum (Blanksby et al., 2011) into the wall while setting the body in the correct position to turn during the approach phase. Indeed, maintaining a horizontal swimming velocity as high as possible is a decisive ingredient in obtaining a high angular velocity during the rotation phase.

Theoretically, swimming velocity is determined by stroke length (SL) and stroke rate (SR) and has been used to identify spatial-temporal and pacing strategy (Seifert et al., 2005); therefore, it is important to discuss results in variations of stroking characteristics during approach to the wall. In the current study, there was no significant main effect of the turning technique on SL and SR over the intervention period. Age-group swimmers increased SR in proportion to approaching speed, from 7.5 m to 2.5 m, but decreased SL across all turning techniques over the intervention period. Both SR and SL ranges of breaststroke to breaststroke turn-in of this age group tended to be consistent with previous studies of the backstroke technique in age-group swimmers at very high intensity (Silva et al., 2013). Consequently, consistency of the SL during backstroke approach is crucial to maintain speed, which could directly relate to turn-in performance.

From the perspective of kinaesthetic awareness, the perception and acquisition of a breaststroke to breaststroke approach would necessitate swimmers seeking and establishing an acceptable proportion between last stroke hand-wall distance and touching depth to transition from supine to prone. The somersault turn had the longest last stroke hand-wall distance and the deepest touching. This implies that age-group swimmers accomplish a backward flip by completely extending their arms, contacting deeper, and quickly rotating their lower limbs around the horizontal transverse axis. The current result in the somersault turn point to the probability that, four-week systematic CI training program may have increased awareness, learning perception, and sense of space during breaststroke to breaststroke turns, which might explain the improvement in last stroke hand-wall distance and touching depth. The evidence from this study points towards the idea that systematic CI training program, in conjunction with a practice environment and appropriate level in the initial stage of learning, appeared to be a key contributor to improving skills (Porter and Magill, 2010)

Regarding the rotation phase, it has been reported that rotation time varies widely across different turning techniques, different orientations and alternating turns and that the ability to perform very fast rotation is a vital requirement that could imply substantial improvements in turning time (Pereira et al., 2015; Puel et al., 2012). According to the temporal analysis in the current study, the rotation phase had the greatest improvement after intervention (~12.3–17.9%). This was an interesting finding since it showed that age-group swimmers should maintain their approach speed while improving their execution of global body movement during rotation to facilitate rotation speed and overall turning performance.Notably, there was no main effect of technique on rotation time, suggesting that the training program was responsible for significantly improving rotation in all breaststroke to breaststroke turning techniques in age-group swimmers. In comparison to the other three turns, the open turn had the fastest rotation time following the intervention period. It is important to note that 90% of the subjects (18 swimmers) preferred the open turn during competition.

Taken together, the current findings appear to support the idea that the open turn is frequently taught before young swimmers learn how to perform more complex turns. Furthermore, in their swimming turn technique, these age-group swimmers had not yet attained optimal adaptation between perceptual-motor abilities and complex and difficult movement (Purdy et al., 2012). Nonetheless, the rotation times in this study were slightly slower than those shown in previous studies on breaststroke turn (1.15 s) (Blanksby et al., 1998), butterfly turn (1.10 s) (Ling et al., 2004), and rollover backstroke turn in age-group swimmers (0.70 s) (Blanksby et al., 2004).

From the perspective of push-off efficiency, it is important to maximize the proportion of the kinematic and kinetic variables that contribute to final push-off velocity. In the current study, two kinematic variables - the tuck index and foot plant index-tended to significantly decrease after the intervention period across all turns. However, there was no significant main effect of technique on tuck index either pre- and post-intervention. In the current study, the tuck index was about 80–83% of swimmers' leg length at pre-intervention and 71–75% at post-intervention. Our results in the current study tended to be higher than those of previous studies for the backstroke rollover turn by 11–15%

(Pearson et al., 1998), 13–17% for the breaststroke turn (Blanksby et al., 1998), and 15% for the tumble turn (Blanksby et al., 1996) and butterfly turn (Ling et al., 2004) in age-group swimmers. Consequently, the results suggest that age-group swimmers may have to bend their knees a little more, as that would directly lead to a lower tuck index (flexed lower limbs). This factor could help achieve an optimal centre of gravity position, create less water resistance during push-off and lead to favourable peak forces to generate impulses (Prins and Patz, 2006; Araujo et al., 2010).

Considering the foot plant index, the highest percentage was found in the somersault turn in both pre- and post-intervention (69 vs. 57 %). Our results have a number of similarities with Puel et al. (2012) findings, about 75% in elite male swimmers, but tended to be higher than those of previous study in university swimmers (45%) (Prins and Patz, 2006). From the hydrodynamics viewpoint, the optimal depth of foot-planting approximately 30–40 cm was strongly related to horizontal push-off force, gliding distance and decreasing hydrodynamic drag (Prins and Patz, 2006; Lyttle et al., 1999). As a result, the fact that the somersault turn produces a higher gliding depth than the other three turns may be related to the greater depth of the foot plant on the wall.

Turning to the kinetic perspective, identifying force-to-time analysis involving the calculation of total wall-contact time, absolute peak 3D forces, and horizontal impulses would provide a better understanding of the wall contact phase features in breaststroke to breaststroke turns. In the current study, the wall contact time was about 0.53–0.60 s and 0.53–0.63 s at pre- and post-intervention, respectively. Despite slightly higher differences in values for the breaststroke turn (0.39s) (Blanksby et al., 1998) and butterfly turn (0.37s) (Ling et al., 2004) by age group, as well as the tumble turn in national level swimmers (0.30s) (Pereira et al., 2015), our findings were consistent with previous studies for the rollover backstroke turn (0.60s) (Araújo, 2007) and the tumble turn (0.58s) (Blanksby et al., 1998) by age group.

The mean percentages of push-off times were about 69% and 73% for pre- and post-intervention across all turns, which is in line with the previous studies on the tumble turn performed by elite swimmers (65–74%) (Pereira et al., 2015, Prins and Patz, 2006;

Lyttle et al., 1999). Given the impact of the force-to-time relationship on the push-off velocity (Blanksby et al., 2004; Prins and Patz, 2006), the correlation between push-off force, total wall contact time and active push-off time is required to maximise push-off velocity. In the current study, the push-off times for age-group swimmers were different at pre-and post-intervention for the somersault (0.38 vs. 0.42s) and crossover turns (0.41 vs. 0.46s), indicating that the training program was successfully responsible for improving a push-off strategy that could assist in producing an optimal push-off performance.

The current study was the first to investigate at three-dimensional push-off kinetics in breaststroke to breaststroke turns performed by age-group swimmers, providing insight into the force-time features of turning technique knowledge. There were no significant differences in lateral (open, bucket and crossover) and ventral (somersault) wall-touching in the medio-lateral peak X force between pre- and post-intervention, and the values were also relatively small (5.6 - 14.8%) compared to the mean horizontal peak Z force. Our findings for the breaststroke to breaststroke transition are similar with previous findings (Araújo, 2007), which found that mean peak X forces during push-off were about 5% to 15% of the mean horizontal Z peak force.

Theoretically, higher medio-lateral (X) and up or down (Y) pushing forces might directly reflect on horizontal push-off force and impulse [20, 25]. The peak Y force in the current study tended to be higher than the one found in a previous study for rollover backstroke turn (Blanksby et al., 2004) by 30% in open turn, 25% in crossover turn, 22% in bucket turn and 16% in somersault turn, respectively. These findings can be attributed to a variety of factors, including differences in rotation execution, the foot plant index at the wall, the preferred technique of the age-group swimmers and the four-week intervention program being not long enough.

Significant differences in peak Z force between pre- and post-intervention were observed in the open turn and the somersault turn. The peak Z force values for lateral pushing (bucket turn, open turn and crossover turn) and ventral pushing (somersault turn) in the current study were quite similar to previous studies' values for female swimmers (open turn: 192.4 ± 34.7 N; bucket turn: 202.4 ± 53.2 N; crossover turn: 178.2 ± 42.2 N) (Purdy et al., 2012). On the other hand, they were relatively smaller compared to those obtained for the rollover backstroke turn (220 ± 70 N) (Blanksby et al., 2004), the breaststroke turn (557.41 ± 109.61 N) (Puel et al., 2012), the butterfly turn (744.4 ± 327.1 N) (Ling et al., 2004) and the tumble turn (693.4 ± 228.1 N) (Blanksby et al., 1996) in age-group swimmers.

We found much lower values for the foot-contact impulse with respect to previous studies on the breaststroke turn (118.81 ± 31.21 Ns) (Blanksby et al., 1998), the butterfly turn (152.9 ± 41.1 Ns) (Ling et al., 2004) and the tumble turn (177.2 ± 50.2 Ns) (Clothier et al., 2000) in age-group swimmers. From the perspective of propulsive impulse, Clothier et al. (2000) underlined that the horizontal impulse can be produced in two different ways: (i) through a high force with a larger contact time or (ii) through a lower force with shorter wall-contact time (Clothier et al., 2000). Our findings seem to show that the lower feet impulse was mainly explained by the lower peak Z force, as our results on wall contact time and feet impulse (0.53–0.63 s; 49.36–57.74 Ns) bear a number of similarities with Blanksby et al. (1998) who found that total wall contact time was 0.60 ± 0.20 s and 55.6 ± 12.4 Ns for the horizontal impulse (Blanksby et al., 2004).

The final push-off velocity for all turns improved significantly over the intervention period, with the highest velocity occurring in the crossover turn (2.11 ± 0.29 $m \cdot s^{-1}$). Even though these results differ from the previously obtained in the rollover backstroke turn (1.70 $m \cdot s^{-1}$) (Blanksby et al., 2004), they are consistent with results obtained on the breaststroke turn (2.01 $m \cdot s^{-1}$) (Blanksby et al., 1998), butterfly turn (2.01 $m \cdot s^{-1}$) (Ling et al., 2004) and tumble turn in freestyle (2.01 $m \cdot s^{-1}$) (Blanksby et al., 1996) among age-group swimmers. However, there were no main effects of turning technique on final push-off velocity after intervention in the current study.

The mean percentage of the turn-out phase relative to the 15 m turning time was approximately 44%, with the fastest turn-out time being found in the bucket turn (7.12 ± 0.86 s) compared to the other three turns. However, there was no significant main effect of turning technique observed on gliding distance, gliding time, breakout distance, breakout time and turn-out time. This was an interesting finding since it revealed that age-group swimmers tended to adopt a consistent pull-out strategy while performing breaststroke to breaststroke turns, implying that the intervention program improved an age-group swimmer's perception of their turn-out ability.

From the perspective of turn-out performance, the main consideration for turn-out performance should be optimizing propulsion force, gliding depth and distance, without decreasing velocity (Termin and Pendergast, 1998). It is important to note that the somersault turn seemed to have longer breakout distance and breakout time than the other turns. The findings might be attributed to how the age-group swimmers use a greater foot-planting depth, higher tuck index, and lower peak Y force as positive determinants of pull-out performance, as they allows the swimmers to spend more time in optimal streamlining to minimize hydrodynamic drag. The depth of the gliding path in the somersault turn was deeper than in the other turns, which was consistent with previous studies and supports the idea that longer gliding takes more time to regain race speed and a glide depth of approximately 0.4–1.0 m for approximately 1 s before initiating kicking is recommended (Clothier et al., 2000; Lyttle et al., 2000).

Conclusions

This study provide insight into the relationship between biomechanical factors in terms of their strategic importance for each backstroke to breaststroke turning technique, and showed that a four-week intervention programme facilitated learning of these turning techniques in age-group swimmers. The 15 m turning time spent after the intervention was mostly observed during turn-in (45%) and turn-out (44%) phases, and the most improved phase was the rotation phase (~12.3%–17.9%). In general, turning performance can be predicted mostly by wall contact and turn-out phases. However, the results suggest that backstroke to breaststroke turn performance may require a good combination of the variation in symmetrical contributions between turn-in and turn-out phases. In addition, the rotation variables (touching depth and rotation time) and wall contact variables (normalised peak force, horizontal impulse and push-off velocity) displayed a significant relationship with turning performance. Remarkably, the evidence in the current study appears to suggest that a swimmer's preferred turn technique is not always superior to its alternatives. Furthermore, a specific training program concerning turning technique skills should be recommended for young swimmers regardless of their experience with learning turning skills.

CHAPTER 7. General Discussions

The turning phase has been recognized as one of the most important parts of competitive swimming events, with possible direct effects on swim race results. To understand the contribution and interaction of biomechanical features of the temporal, kinematic, kinetic, electromyographic and hydrodynamic variables on different turning techniques, theoretical models and exploratory research have been developed (Blanksby et al., 2004; Araujo et al., 2010; Vilas-Boas et al., 2010; Pereira et al., 2015). To facilitate the teaching–learning process, the specificity of training interventions in strengthening learning skills and technical capability of complex turning techniques should be addressed in the context of turning skills developments in young swimmers.

The current Thesis aimed to undertake an exploratory study, carrying out an integrative evaluation by focusing on emerging biomechanical technology, carry on experimental and intervention studies, and using linear and non-linear mathematical approaches to model and predict backstroke to breaststroke turning performance. Researchers have previously recognized and adopted the use of biomechanics technology applications in swimming as a key tool for optimizing and maximizing precise and effective quantitative data analysis (Barbosa et al., 2015). The technologies used in current study were fully integrated with a 3D motion capture system using customised underwater tri-axial force plates electromyographic (EMG) activity and hydrodynamic variables were assessed using an inverse dynamic approach.

Training approaches, especially in young swimmers, offer useful information on the magnitude of skill development and perceptual–motor adaptability. In this study, age-group swimmers took part in a four-week systematic contextual interference training program that included 16 training sessions of 40-min duration. Swimmers practiced a blocked-type training plan schedule from the first to fourth session (each one focusing on a separate turning technique) and a serial plan schedule from the fifth to eighth session (i.e. the series of sequenced open, somersault, bucket and crossover turns was repeated for 10 min in each turning technique: 4 x 10 min). From the 9th to the 12th sessions, a serial plan schedule was adopted, but with two "laps" (i.e. the following sequence of open, somersault, bucket, and crossover turns lasting 5 minutes in each turning technique was repeated twice: 2 (4 x 5 min)). A random schedule was followed in the 13th to 16th training sessions, with an equal number of trials for each turning technique.

This Discussion chapter summarizes and integrates the key outcomes from each chapter experimental. **Chapter 2** identified the biomechanical features associated with overall turning performance to characterize age-group swimming turns and identify key parameters that would influence backstroke to breaststroke performance. The aim of **Chapter 3** was to determine and compare the iEMG activity and kinematic variables of open, somersault, bucket and crossover backstroke to breaststroke turning techniques, with an emphasis on rotation and push-off efficacy. **Chapter 4** identified and compared hydrodynamic characteristics and pull-out strategy, while **Chapter 5** considered to predict 15 m turning performance using and comparing linear regression and tree-based machine learning models from selected features of kinematic-temporal, kinetic and hydrodynamic variables. The goal of **Chapter 6** was to investigate the biomechanical characteristics of four different backstroke to breaststroke turning techniques after a four-week contextual interference program with age-group swimmers.

Turning performance has been defined as the capability to transition between turn-in and turn-out phases (Blanksby et al., 2004; Puel et al., 2012). Furthermore, a very quick approach and rotation combined with an explosive push-off, as well as optimizing underwater timing and distance, seem to be important in facilitating total turning performance (Blanksby et al., 2004; Prins and Patz, 2006; Vilas-Boas et al., 2010; Puel et al., 2012). As a consequence, learning how to improve faster turns would not provide a comprehensive relevant scenario without a deeper understanding of the related biomechanics characteristics and complex interactions between the difference turning phases. As a result, we started by verifying and identifying the element and feature biomechanics variables that are related and contribute to the overall turning performance (**Chapter 2**). Biomechanics variables were classified as turn-in (approach with rotation phase) and turn-out phase (wall contact with the gliding and pull-out phases). This grouping method was chosen because it is one of the most feasible ways for thoroughly characterize and predict statistical methods for obtaining reliable results and it determined the 'best' regression equation of total turning efficacy (Tor, Pease and Ball, 2015).

Turn-in variables (7.5 m time, 2.5 m time, average stroke length and rotation time) were found to account for 88, 77, 89 and 87 % of the difference in open, somersault, bucket and crossover turns, respectively. Our findings are consistent with those of Nicol et al. (2019) and Mason and Cossor (2001), who found that the turn-in phase had a direct impact on total turning performance, especially in elite and Olympic swimmers. In the turn-out phase, key variables generated mixed findings in terms of the various kinematic and kinetic characteristics at the push-off phase, which may have been accounted for the pull-out strategy, and different tendencies of turn-out performance were observed. Kinematic–temporal (wall contact time, foot plant index, final push-off velocity, first gliding distance, first gliding time, second gliding depth, breakout distance and breakout time), kinetic (peak push-off Y and Z forces) and hydrodynamic variables (first gliding drag coefficient and first and second gliding drag forces) variables independently accounted for 93, 92, 92 and 90% of variance in open, somersault, bucket and crossover turns. These findings are in agreement with those of Havriluk (2005) and Naemi et al. (2010), and they extend support to the idea of optimizing the interrelationships between kinematic, kinetic and hydrodynamic variables that could have a significant impact on turn-out performance (Termin and Pendergast, 1998; Vilas-Boas et al., 2010; Pereira et al., 2015).

According to the findings of the current study, age-group swimmers require a good combination and balanced contributions between turn-in and turn-out segments, which will result in directly improved 15-m turn time performance. Regardless, variations in biomechanics features between turning technique can have individual beneficial and preference effects of a specific turning technique, as shown in a previous analysis on national-level swimmers (Pereira et al., 2015). As a result, specialized training should be structured primarily based on the key biomechanics characteristic of each technique, representing priority areas that can be specifically trained to increase turning proficiency.

Findings (**Chapter 2**) revealed that rotation time is a kinematic variable that may better explain turn-in and total turning performance. As a result, the four backstroke to breaststroke turning techniques respective rotation movements can be closely related to the variance in kinematic–temporal properties and neuromuscular contributions. From a neuromuscular perspective, individual EMG behaviour in swimming turns may provide relevant information on various muscle recruitment and activation patterns, especially during the rotation and push-off phases (**Chapter 3**). Thus, the iEMG and total iEMG (TiEMG) were used to compare among the four turning techniques and to verify the relationships between the iEMG and selected rotation and push-off efficacies. We hypothesised that the EMG response of the lower limb and core muscles during the rotation and push-off phases would be sensitive to the different backstroke to breaststroke turning techniques. Despite this, findings partially disagreed with the established assumptions. Different turning techniques tended to be dependent on rotation time, but iEMG activity, as a potential determinant of rotation and push-off efficacy, could not be distinguished. However, our observations are similar with those of Pereira et al. (2015), who discovered that the behaviour of the muscles selected for EMG analysis was quite similar among the four studied different flip turn techniques.

Interestingly, there were no statistically relevant variations between the turns in terms of global body rotational movement, meaning that the basic characteristics potentially influencing individual turning performance should be carefully examined. As far as we know, this is the first time iEMG characteristics have been considered in this context and TiEMG was expressed as a percentage of iEMGmax to normalize the result per unit of time for each rotation and push-off phase among the four studied turning techniques. The crossover and modified roll turns had the highest rotation and push-off iEMG values, with the erector spinae and gastrocnemius having the highest activation values during the rotation and push-off phases. Our findings are consistent with those of Pereira et al. (2015), providing further support for the significance of core muscle contributions during the rotation and push-off phases. Furthermore, data gathered from the EMG action of backstroke to breaststroke turns can have direct implications for selecting appropriate exercises and developing training programs for optimizing this specific section of medley races.

The exploratory research on swimming turns emphasizes that increased push-off and turn-out effectiveness result in improved total turning performance (Lyttle et al., 2000; Prins and Patz, 2006; Naemi et al., 2010). We addressed fundamental questions about the characteristics and pull-out strategy of the four backstroke to breaststroke turning techniques by comparing the hydrodynamic characteristics and pull-out strategies of the four backstroke to breaststroke turning techniques (**Chapter 4**). The hydrodynamic characteristics, including speed-dependent (drag force and drag coefficient) parameters and swimmer's body shape (cross-sectional area: S), tended to correlate, despite with low values identified at the first gliding position rather than the second gliding position. The same tendency was observed in the four backstroke to breaststroke turns. Our findings are consistent with previous data using inverse dynamics (Vilas-Boas et al., 2010) and computational fluid dynamics methods (Costa et al., 2015).

The pull-out strategy yielded chosen by consistent pacing and distance travelled that were irrelevant to distinguish the backstroke to breaststroke turning technique used. Our findings supported previous ones where the optimum timing of the pull-out technique is dependent on each individual strategy (Termin and Pendergast, 1998) and that the difference in lateral and ventral gliding positioning may not be the primary source of turn-out performance diversity (Lyttle et al., 2000). About the fact that the data did not provide for the classification of the most effective turning strategies in terms of backstroke to breaststroke turn-out performance, there are possible explanations to better explain related variables as well as hydrodynamic and pull-out characteristics to increase turning performance. The crossover turn's push-off velocity was likely higher than the other turns because of the faster turning and rolling, combined with pushing at lateral body positioning, which may directly impact optimizing the push-off velocity (Araujo et al., 2010; Pereira et al., 2015).

The somersault turn exhibited less gliding depth than any other turn, which could be attributed to the lower foot plant position during push-off, which could be directly responsible for the glide depth path (Lyttle et al., 2000; Prins and Patz, 2006). As a consequence of the theoretical foundation and experimental findings, the faster turn-out time of the backstroke to breaststroke turn should be obtained from the combination of the push-off phase and the optimum depth of the gliding phase. Furthermore, regardless of age-group swimmers preference for a backstroke to breaststroke turning technique, they should focus on maintaining a streamlined posture and selecting the appropriate gliding time and distance.

Because of the diversity and complexity of data sources, the relationship and contribution of each biomechanical domain and the need for an adequate research design and statistical approach, modelling and predicting turning output is complicated (Mullineaux, Bartlett and Bennett, 2001; Barbosa et al., 2010). The principle of research design and statistical methodology is often directed to a linear modelling approach, yet, this may not be sufficient to explain the dynamics of complex movement. In the case of swimming turns, no single variable has strongly predicted turn outcomes (Nicol, Ball and Tor, 2019) and linear regression over fitting occurs when the model is too complex. Minimizing over fitting is one of the primary goals of machine learning, according to structural equation modeling (Domingos, 2012; Yarkoni and Westfall, 2017; Richter, O'Reilly and Delahunt., 2021). Cross validation is especially beneficial when a model's complexity (Yarkoni and Westfall, 2017) affects its accuracy and classification success when applied to new or novel scenarios (Halilaj et al., 2018; Marcot and Hanea, 2020). Surprisingly, explicit cross-validation of complicated swimming turn models has not been adequately documented and is nearly totally absent from swimming science.

In Chapter 5, two linear models (LASSO and RIDGE) and seven different decision tree–based models (a single decision tree: TREE, a random forest algorithm: RF, AdaBoost: ABST, Gradient boosting: GBST, Extra trees: XTREE, Extreme gradient boosting: XGBST, and quantile random forest: QRF) were used to identify the performance determinant factors to predict 15 m turning backstroke to breaststroke turning performance, based on the values of the coefficient of determination (R^2) and mean squared error (MSE), using three types of cross-validation including leave-one-out cross validation (LOOCV), 5-fold cross validation and 10-fold cross validation.

The two linear models (LASSO and RIDGE) and machine learning algorithms using seven tree-based models (TREE, RF, ABST, GBST, XTREE, XGBST and QRF) approaches were able to predict the four different backstroke to breaststroke turning performance. In addition, the leave-one-out cross-validation (LOOCV) is appropriate and robust to estimate of backstroke to breaststroke turns model performance regarding the small dataset (n=40 variables) (Marcot and Hanea, 2020). The findings provide an important step toward insights into the characteristics and interrelationships of biomechanical determinants on four backstroke to breaststroke turning performance in age-group swimmers. Furthermore, the Lasso, Ridge, and ABST models suggested that balanced contributions between the turn-in and turn-out phases should be attained for best turning performance.

The inclusion of the two temporal variables (average SR and SL) during turn-in satisfactorily matched those studied by Seifert et al. (2005) and Nicol, Ball and Tor (2019) in freestyle; the results also support the previous findings available in literature, which showed that the swimming speed and momentum into the wall are related to pacing strategy and turning performance (Blanksby et al., 2004; Seifert et al., 2005; Nicol, Ball and Tor, 2019). Machine learning model outputs indicated that proper streamline posture and breakout distance resulted in turn-out performance, which was consistent with previous researches and indicates that gliding efficiency and an optimum pull-out strategy are important for turning performance (Naemi et al., 2010; Vilas-Boas et al., 2010). Furthermore, the results emphasize the importance of strengthening its maintaining approaching speed in conjunction with the symmetric powerful extension push-off force of lower limbs, hydrodynamic underwater posture, and gliding efficacy, all of which are becoming increasingly important to turning performance.

Understanding the factors that contribute to superior turning performance would not provide a complete kinetic picture without a deeper understanding of the complex interaction between the key biomechanical variables. We used multifactorial analysis in **Chapters 2-5** to investigate and identify the interaction and contribution of each biomechanical domain to turning performance.The effective intervention research was then used to gain insight into the complex training process that could be affected by learning, consolidating and gradually improving backstroke to breaststroke turning abilities. The aim of **Chapter 6** was to investigate the biomechanical characteristics of four different backstroke to breaststroke turning techniques during an intervention program, as well as how personal preferences for turning techniques respond to the training program. To facilitate skill learning, subjects were trained over a four weeks period in 16 systematic contextual interference training sessions with increasing complexity (Guadagnoli and Lee, 2004).

Findings provide important evidence for the impact of a specific training program on swimmers' learning and development of the ability to generate different techniques of the backstroke to breaststroke turning performance. We found that an intervention program that gradually increases contextual interference improves the learning process of backstroke to breaststroke turning techniques. Over the intervention period, the 15 m turning time for all turns was significantly improved, with the highest improvement found in the somersault turn, followed by open, crossover and bucket turns, in that order. The most significant observation from the data was that the open turn was the preferred turning technique (>90%) of the age-group swimmers in this study and the intervention program enabled for the reduction of the preferred technique's effect on performance. These findings support previous findings on swimming starts (Blanksby, Nicholson and Elliott, 2002; Nicol, Ball and Tor, 2019) and have increased our confidence that the preferred technique is not always superior to other; additionally, age-group swimmers were able to improve turning performance through specific training sessions.

As previously mentioned **(Chapter 2),** the rotation time may have influenced total turning performance by revealing different muscle recruitment and activation patterns, especially during the rotation and push-off phases (**Chapter 3**). Age-group swimmers improved the most in mean time spent in the rotation period between pre- and post-intervention results, but no differences were observed in the wall contact phase among the turns. The open turn has the fastest rotation time, demonstrating that rotation time varies considerably based on turning technique and task difficulty and that learner experiences may have directly influenced the ability to learn complicated movements

(Guadagnoli and Lee, 2004; Prins and Patz, 2006). The wall contact phase characteristics observed are consistent with previous results in the flip turn techniques, where the kinematic and kinetic variables demonstrated no distinguishable variations between the four flip turn techniques studied (Pereira et al., 2015).

According to the evidence presented in a previous chapter (**Chapter 4**), the different turning techniques used have very little impact on the hydrodynamic characteristics or pull-out strategy. According to the results of the current research, age-group swimmers used a consistent pull-out strategy when doing backstroke to breaststroke turns (**Chapter 6**). As a result, it should be assumed that the individual training program consistently improved the turn-out performance of age-group swimmers.

CHAPTER 8. Conclusions

The results from the series of studies in this thesis emphasize the importance of exploratory research, an integrative evaluation through emerging new biomechanical technologies, combine experimental with learning methods and employ a statistical approach to analyze, model and predict the backstroke to breaststroke turning action. From the sectorial findings, the following general conclusions were drawn:

(i) The four-week intervention program, which offers systemic increases in contextual interference, facilitates age-group swimmers to learn and improve the ability to perform different technique of the turning performance. However, four weeks did not take long enough to classify one technique as the most improved and proficient technique;

(ii) The 15 m turning time for all the turning technique were improved significantly over the intervention period, with the greatest percentage improvements found in the somersault turn, followed by the open, crossover and bucket turns (4.8 – 5.3%);

(iii) The kinematic–temporal variables (v, SR, SL, approach time and rotation time) appeared to be more important during turn-in, while the kinetic variables were more relevant during turn-out, emphasizing the significance of the pushing-against-the-wall phase;

(iv) The crossover turn had the greatest rotation and push-off iEMG values. The turning technique neuromuscular behaviour was very similar with the erector spinae show the highest activity during the rotation process, while biarticular gastrocnemius medialis and monoarticular tibialis anterior were primarily activated during the push-off phase. However, across all turning strategies observed, there were no relationships between TiEMG and selected kinematic variables during the rotation and push-off phases;

(v) The hydrodynamic characteristics (D, S and C_D) obtained for the first gliding position were slightly lower than the corresponding values obtained for the second gliding position. The pull-out strategy was independent, with the four turning techniques exhibiting the same tendencies in terms of time spent and breakout distance;

(vi) The linear LASSO approach using leave-one-out cross-validation was found to be appropriate and robust for predicting the 15 m backstroke-to- breaststroke turns performance in open and somersault technique and the linear RIDGE approach was found to be appropriate and robust for predicting the bucket turn. The machine learning algorithms based on an ABST tree-based model using leave-one-out cross-validation was found to be appropriate and robust for predicting the 15 m in crossover turn;

(vii) A faster turn necessitates a well-balanced strategy for turn-in and turn-out. Consistency in approaching speed, which results in an optimized stroke rate and stroke length and faster rotation, can result in a faster turn-in. Age-group swimmers should focus on correctly performing the push-off phase, reaching optimum gliding depth and determining the appropriate gliding time and distance;

(viii) The preferred turn technique was not always advantageous and turning practice sessions enabled age-group swimmers improve their turning performance.

CHAPTER 9. Suggestions for future research

Overall, this thesis integrated motor learning concepts into biomechanics research though considering exploratory intervention analysis. The integrative evaluation is an appropriated approach for properly understanding the use of biomechanical knowledge in the effective transition of the backstroke to breaststroke techniques during medley events. Based on our key findings, it is critical to continue research, especially by pursuing these ideas:

(i) To address the methodological challenges of research on exploratory intervention and more well-controlled studies, a control group with retention and transfer of turning skills needs to be considered;

(ii) Conducting large-scale, group-based study by extending the comprehensive analysis of kinematic-temporal, kinetic, hydrodynamics, and electromyographic analysis and comparing swimmers of varying skill level and gender to expand on the existing research results;

(iii) Considering that the relationships established between swimming performance variables are not always linear, modeling and predicting the comprehensive temporal, kinematic, kinetic, electromyographic, and hydrodynamic determining factors for each backstroke to breaststroke turn using machine learning (Ml) algorithms with difference cross-validation should be taken into account and implemented;

(iv) It is crucial to deepen the integration of full-body tracking, intramuscular coordination, and computer simulation in order to understand and recognize the keys of complex rotation and pivot movements;

(v) The FINA rules for breaststroke pull out were revised to allow swimmers to do a dolphin kick at any time rather than subtly separating their hands before the kick (SW 7.1). The integrative study of hydrodynamics, kinematics, and electromyography in different sequences of upper and lower extremity actions during transition related to pull-out results must be discussed;

(vi) Analyze the effects of strength and conditioning training programs on the specialized closed kinetic chain of the lower limb during the push-off phase, strengthening core muscles to increase the efficacy of muscle coactivation to speed up rotation should be considered, as should potential research opportunities.

CHAPTER 10. References

Chapter 1

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Chapter 2

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Chapter 7

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