INTERPRETATION OF PROPULSIVE FORCE IN TETHERED SWIMMING THROUGH PRINCIPAL COMPONENT ANALYSIS

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INTERPRETAÇÃO DA FORÇA PROPULSORA NO NADO ESTACIONÁRIO ATRAVÉS DA ANÁLISE DO COMPONENTE PRINCIPAL

INTERPRETACIÓN DE LA FUERZA PROPULSORA EN EL NADO ESTACIONARIO A TRAVÉS DEL ANÁLISIS DEL COMPONENTE PRINCIPAL

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ABSTRACT

Introduction: Propulsive force in swimming, represented through impulse, is related to performance. However, since the as different biomechanical parameters contribute to impulse generation, coaches have a difficult task when seeking for performance improvement. Objective: Identify the main components involved in impulse generation in the front crawl stroke. Methods: Fourteen swimmers underwent a 10-second all-out fully tethered swimming test. The following parameters were obtained from the force-time curve: minimum force, peak force, mean force, time to peak force, rate of force development and stroke duration. This stage was followed by a principal component analysis. Results: The principal component analysis showed that component 1, predominantly kinetic, was composed of peak force, mean force and rate of force development, and accounted for 49.25% of total impulse variation, while component 2, predominantly temporal, composed of minimum force, stroke duration, and time to peak force, represented 26.43%. Conclusion: Kinetic parameters (peak force, mean force, and rate of force development) are more closely associated with impulse augmentation and, hypothetically, with non-tethered swimming performance. ***Level of Evidence II; Diagnostic studies - Investigating a diagnostic test.***

Keywords: Swimming; Mechanics; Biophysics; Multivariate analysis.

RESUMO

Introdução: A força propulsora na natação, representada através do impulso, está relacionada ao desempenho. Entretanto, já que diferentes parâmetros biomecânicos contribuem para a geração do impulso, os treinadores têm uma difícil tarefa ao buscarem a melhora do desempenho. Objetivos: Identificar os principais componentes envolvidos na geração do impulso na braçada do nado crawl. Métodos: Catorze nadadores foram submetidos ao teste de nado estacionário, totalmente all-out, com duração de 10 segundos. Os parâmetros de força mínima, força máxima, força média, tempo para força máxima, taxa de desenvolvimento da força e a duração da braçada foram obtidos a partir da curva força-tempo e, depois, foi realizada uma análise do componente principal. Resultados: A análise do componente principal revelou que o componente 1, predominantemente cinético, era composto pelos parâmetros de força máxima, força média e taxa de desenvolvimento da força e contava com 49,25% da variação total do impulso, enquanto que o componente 2, predominantemente temporal, composto pelos parâmetros de força mínima, duração da braçada e tempo para força máxima, representava 26,43%. Conclusão: Os parâmetros cinéticos (força máxima, força média e taxa de desenvolvimento de força) estão mais associados ao aumento do impulso e, hipoteticamente, ao desempenho no nado não estacionário. ***Nível de Evidência II; Estudos diagnósticos - Investigação de um exame para diagnóstico.***

Descritores: *Natação; Mecânica; Biofísica; Análise multivariada.*

RESUMEN

Introducción: La fuerza propulsora en la natación, representada a través del impulso, está relacionada al desempeño. Entretanto, ya que diferentes parámetros biomecánicos contribuyen para la generación del impulso, los entrenadores tienen una difícil tarea al buscar la mejora del desempeño. Objetivos: Identificar los principales componentes involucrados en la generación del impulso en la brazada del nado crawl. Métodos: Catorce nadadores fueron sometidos al test de nado estacionario, totalmente all-out, con duración de 10 segundos. Los parámetros de fuerza mínima, fuerza máxima, fuerza promedio, tiempo para fuerza máxima, tasa de desarrollo de la fuerza y la duración de la brazada fueron obtenidos a partir de la curva fuerza-tiempo y, después, fue realizado un análisis del componente principal. Resultados: El análisis del componente principal reveló que el componente 1, predominantemente cinético, era compuesto por los parámetros de fuerza máxima, fuerza promedio y tasa de desarrollo de la fuerza y contaba con 49,25% de la variación total del impulso, mientras que el componente 2, predominantemente *temporal, compuesto por los parámetros de fuerza mínima, duración de la brazada y tiempo para fuerza máxima, representaba 26,43%. Conclusión: Los parámetros cinéticos (fuerza máxima, fuerza promedio y tasa de desarrollo de fuerza) están más asociados al aumento del impulso e, hipotéticamente, al desempeño en el nado no estacionario.* ***Nivel de Evidencia II; Estudios diagnósticos - Investigación de un examen para diagnóstico.***

Descriptores: *Natación; Mecánica; Biofísica; Análisis multivariante.*

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INTRODUCTION

Propulsive force in swimming is paramount for performance.[1] Therefore, efforts have been made to seek effective, reliable and practical means of assessing and monitoring changes in this capacity. In this context, fully tethered swimming[2] is used in the routine of competitive teams.[3]

Although fully tethered swimming involves absence of drag[4] and velocity, and changes may occur in the duration, trajectory and velocity of the segments,[5] studies have shown similarity with conventional swimming,[6-8] as well as sensitivity in the identification of training-induced adaptations.[9]

Fully tethered swimming allows the quantification of distinct biomechanical parameters.[3,4] However, impulse seems to be the best at expressing propulsive force, as it represents the variation in linear motion quantities,[10] conjugating kinetic and temporal characteristics throughout the movement cycle.

In fact, this parameter has been considered in regression models that included it as a swimming performance predictor variable,[2-4] regardless of the competitive level and/or style of the athletes assessed, similar to the findings recorded in running[11] and jumping.[12]

Knowing that impulse is calculated by the product of force and time, visualized from the area under the force-time curve,[10] changes in impulse, in swimming, are subject to the modification of the following five fundamental parameters:[1] minimum force, force generated at the start of the propulsive action,[2] peak force, largest magnitude of force generated in the propulsive action,[3] time to peak force and rate of force development,[4] and duration of the propulsive action.[4]

Any of these can alter the impulse, and consequently the performance, magnitude. Corroborating this observation, Rasulbekov et al.[13] verified a performance improvement of a swimmer with concomitant modification of peak force and time to peak force.

In view of this scenario, a question that arises is related to the contribution of these parameters to performance in tethered swimming (in the expression of impulse), which, although important, has not been investigated. It should be noted that although bivariate relationships between swimming velocity and the abovementioned parameters have been reported[2,3,14-18] in complex and redundant phenomena such as swimming, analyzing parameters separately (e.g., through bivariate correlation analysis) does not seem to be the most suitable approach,[19,20] since the interaction of these parameters is not considered.[19,20]

In addition, the use of a multifactorial approach could indicate interaction between the factors and impulse, allowing better targeting of intervention procedures, a *posteriori*, for optimization of performance.

Thus, the aim of this study was to identify, through the biomechanical parameters extracted from the force-time curve of tethered swimming, the latent dimensions that would contribute most to the generation of impulse in fully tethered swimming.

MATERIALS AND METHODS

The sample consisted of 16 experienced (7.8 ± 2.1 years) male swimmers (age: 18.6 ± 1.3 years, height: 1.8 ± 0.09 m; body mass: 74.3 ± 2.3 kg). The competitive level was defined according to Barbosa et al.,[21] who considered the minimum indices adopted by the entities responsible for participation in the Senior category 100m freestyle race at international, national and state level during the year in which the research was carried out; in this case, indices established in the year 2016. Swimmers achieved times of 53.12 ± 2.36s and were ranked at national level. After receiving an explanation of the procedures and risks/benefits of the research, the volunteers signed the informed consent form, approved beforehand by the Institutional Review Board of Universidade Anhembi Morumbi (Certificate of Submission for Ethical Appraisal no. 60565916.4.0000.5492, protocol number 101611/2016) with a description of the investigational procedures.

The procedures/tests were carried out in the week prior to the major competition of the season, on a single day, at the usual training time and place. All athletes employed the front crawl stroke. A minimum interval of 24 hours was observed between the end of the last training session and the beginning of the tests, during which period athletes were instructed to maintain their usual diets. Warm-up was standardized at 10 minutes of dryland dynamic stretching, 10 minutes of submaximal-effort swimming, and four maximum intensity 15-meter swims every 2 minutes. After this, each athlete swam 100 meters at a low intensity.

Propulsive force was measured by means of the fully tethered swimming method composed of a load cell with a maximum nominal load of 2000 N (±0.29 N), tied to the athlete's hip by a system of cables and to the starting block by an aluminum bracket. The cable system was attached at a distance of approximately three centimeters from the waterline.

The test consisted of two 10-second maximum effort trials at a maximum intensity. The decision was made to measure the force produced by arms and legs concomitantly, at a self-selected frequency, with the swimmers holding their breath so as to minimize changes in swimming mechanics,[22] thereby approaching conventional swimming conditions.[21]

The trials involved the adoption of a four-minute interval to limit possible fatigue-related interferences. No familiarization process was undertaken as the athletes already underwent the procedure frequently during training sessions.

After being attached to the system, the athletes swam at a moderate intensity until they heard the first audible signal emitted by the evaluator. The athletes then swam at a maximum intensity until they heard a second signal, indicating the end of the test. There was a one- to two-second interval between the emission of the first audible signal and the initiation of force data acquisition.

Leg kicking was seen to produce constant force throughout the test. Furthermore, as we are aware of the fact that the upper limbs account for approximately 85% of the total propulsive force in front crawl swimming,[1] the oscillation between two minimum and consecutive force values was attributed predominantly to the action of a stroke.

In each trial, all the arm strokes performed within a 10-second interval were analyzed separately,[3,21] and we extracted the parameters that could influence impulse, a procedure similar to that adopted by Ugrinowitsch et al.[23] and Andrade et al.[24]

The following biomechanical parameters were considered:

- Minimum Force ($_{min}F$): the lowest force value found in propulsive action. It is the result of an intracycle variation of propulsive force[18] and was used to define the start of each stroke ($_{min}F1$, $_{min}F2$, $_{min}F3$ ...); expressed in N.
- Peak Force ($_{peak}F$): the highest force value found in the stroke; expressed in N.
- Mean Force ($_{mean}F$): mean force generated throughout the stroke; therefore, between two instants of $_{min}F$ ($_{min}F1$ and $_{min}F2$, $_{min}F2$ and $_{min}F3$ ...); expressed in N.
- Stroke duration (DUR): time elapsed between two instants of $_{min}F$ ($_{min}F1$ and $_{min}F2$, $_{min}F2$ and $_{min}F3$ ...); expressed in milliseconds (ms).
- Time to peak force ($T_{peak}F$): time elapsed between $_{min}F$ and $_{peak}F$ (ΔF); expressed in milliseconds (ms)
- Rate of force development (RFD): ratio between the variation of force ($\Delta F = {}_{peak}F - {}_{min}F$) and $T_{min}F$; expressed in $N{\bullet}s^{-1}$
- Impulse (ImpF): integral of the force-time curve between two instants of $_{min}F$ ($_{min}F1$ and $_{min}F2$, $_{min}F2$ and $_{min}F3$ ... $_{min}F8$ and $_{min}F9$), calculated using the trapezoidal rule; expressed in N•s.

For analysis purposes, each parameter was represented by the mean of the values found in the strokes analyzed.[21]

The signals were acquired at a sampling frequency of 600 Hz and were flattened by a fourth-order butterworth filter with a cut-off frequency of seven hertz, defined by residue analysis.[25] The conversion of the digital signal into units of force (N) was achieved using the regression equation obtained previously in a calibration procedure, with increments of 20 kg, up to the maximum load of 100 kg.

Statistical analysis

Data normality was tested by means of the Shapiro Wilk test and the mean and standard deviation were used as a measure of central tendency and dispersion, respectively. In order to identify how the parameters would contribute to swimming we used a factor analysis, a technique guaranteed to be adequate by Bartlett's sphericity test.

Having assumed the convenience of the model, the multivariate principal component analysis was selected. Considering that impulse should be explained mainly by kinetic and temporal parameters, we opted for principal component analysis based on the fixed generation of two components, and original matrix rotation using the varimax method. The data were processed by the statistical package SPSS for Windows (Version 18.0; SPSS, Inc., Chicago, IL).

RESULTS

The descriptive values of the parameters obtained are shown in Table 1.

The principal component analysis revealed that component 1 accounted for 78.44%, with the highest load caused by $_{peak}F$, $_{mean}F$ and RFD, which was designated predominantly kinetic component.

Component 2 accounted for 21.56% of the variation, with the highest load attributed to $_{min}F$, DUR and $T_{peak}F$, and was designated a predominantly kinetic component.

The levels of association between the parameters and the retained components are shown in Table 2.

Table 1. Mean and standard deviation (SD) of peak force ($_{peak}F$), mean force ($_{mean}F$), impulse ($I_{mp}F$), rate of force development (RFD), stroke duration (DUR) and time to peak force ($T_{peak}F$).

	$_{peak}F$ (N)	$_{mean}F$ (N)	$I_{mp}F$ (N•s)	RFD ($N{\bullet}s^{-1}$)	DUR (s/1000)	$T_{peak}F$ (s/1000)
Mean	269.68	134.86	88.11	691.71	647.12	328.77
SD	17.20	7.10	10.60	82.17	64.00	33.01

Table 2. Matrix of components obtained in tethered swimming.

	Component	
	1	2
Variation explained for each component	**78.44%**	**21.56%**
$_{peak}F$	0.74	0.38
$_{mean}F$	0.91	0.24
RFD	0.87	0.34
DUR	0.21	0.82
$T_{peak}F$	-0.18	0.83

DISCUSSION

The aim of this study was to identify, through the biomechanical parameters extracted from the force-time curve, components that would contribute most to the generation of impulse, since this would be related to performance in conventional swimming.

The results show that 78.44% of impulse produced can be explained by the parameters $_{peak}F$, $_{mean}F$ and RFD; hence these are predominantly kinetic characteristics. Therefore, impulse modification in competitive swimmers appears to be closely associated with these parameters.

Despite the importance of the result and its applicability to the performance analysis and interpretation in tethered swimming, given the absence of hydrodynamic drag,[4] there are limitations regarding the extrapolation of these results to performance in conventional swimming. However, in a hypothetical situation of increased stroke impulse and maintenance/stability of total hydrodynamic drag, these help to understand results published in the literature that did not report significant correlations between $_{peak}F$ and swimming velocity in competitive swimmers.[2,3,17] To this end, it is pertinent to consider that although $_{peak}F$ may greatly contribute to impulse generation and performance, as indicated in the literature,[15,16,26] this may not be the discriminating factor of performance in high level competitive swimmers.

This interpretation is consistent with the findings of Rasulbekov, Fomin, Chulkov and Chudovsky,[13] who encountered, parallel to the increase in swimming performance and $_{peak}F$, a concomitant modification of time to peak force. Thus, $_{mean}F$ would be the parameter with the highest impulse-determining load in high level competitive swimmers, rather than $_{peak}F$. The values of correlation found in $_{peak}F$, rate of force development (RFD) and $_{mean}F$ with impulse, which were, respectively, 0.71, 0.91 and 0.87 (TABLE 2), corroborate this idea.

The results therefore indicate that for competitive swimmers it is important to produce high $_{peak}F$ magnitude, but even more important to generate this force as soon as possible, thereby enabling a greater generation of force for longer, and consequently, an increase in $_{mean}F$. These results differ from those found in regional and state swimmers, who appear to depend more on $_{peak}F$ for the development of swimming velocity.[15,16] These differences demonstrate the importance of considering the competitive level of swimmers in investigations, inferences, and generalizations of results appropriately. It also shows that the contribution of the parameters depends on the competitive level, possibly in association with the technical differences between athletes of a higher competitive level and their less qualified peers.

Regarding the rate of force development (RFD), we should remember that as this parameter is obtained by the force variation (ΔF) to time to peak force (Δt) ratio, it would be influenced by both predominantly temporal factors (component 2), such as $_{min}F$ and $T_{peak}F$, and by predominantly kinetic factors (component 1), such as $_{peak}F$. This condition could lead to conflict in both the interpretation of the contribution of RFD to impulse, and in training load control and monitoring routines. However, in the condition studied here, RFD was influenced more by $_{peak}F$ than by $_{min}F$ and $T_{peak}F$. Justifying this observation, RFD had a higher value of correlation in component 1 (0.87) than in component 2 (0.34), and is regarded as a predominantly kinetic parameter.

On the other hand, component 2 was accountable for 26.43% of impulse. This lower "likelihood" of explanation of the variation may have occurred because of less temporal variation of arm strokes in high-level competitive athletes, such as the sample analyzed.

It has already been demonstrated that there is no statistically significant difference between the relative contribution of the propulsive phase in conventional swimming in swimmers and triathletes;[27] therefore, there are slight variations among individuals in the in-water phase. In addition, it is important to consider the relative homogeneity of factors related to the environment (zero body drag due to null velocity), task (tethered swimming at a maximum intensity and without breathing) and individual (sex, competitive level and anthropometry), found in this study. Under these conditions, both the absolute and relative duration of the stroke phases tend to have more moderate interindividual variations.[28]

Hence, without a significant variation of the time factor, parameters such as DUR have less influence on impulse generation. However, the possibility of changes in the contribution of this temporal component due to modifications in the abovementioned factors (environmental, task and individual), cannot be ruled out.

In any case, the results obtained ratify these arguments, since, considering component 2 (TABLE 2), we found a correlation value of 0.83 between $T_{peak}F$ and impulse, and of 0.82 between DUR and impulse. Therefore, since the DUR of the in-water stroke phase (parameter measured in tethered swimming) appears to be less sensitive to modification, athletes would need to produce greater force magnitude for as long as possible during the propulsive action, precisely to produce an increase in $_{mean}F$ and impulse.

Considering the results found, it is possible to admit that although it is important for swimmers to produce considerable magnitude of force ($_{peak}F$), the rapid production of this force and its application over a longer period of time throughout the in-water phase emerge as a possible explanation for the fact that high level competitive swimmers have significantly higher stroke length[29] and swimming velocity values, even with a shorter total stroke cycle, aerial phase and in-water phase duration.

CONCLUSION

Predominantly kinetic parameters ($_{peak}F$, $_{mean}F$ and RFD) are more closely associated with an increase in impulse and, hypothetically, with performance in conventional swimming. Nevertheless, considering the limitations of extrapolation of responses of tethered swimming to conventional swimming, and that the relationship of the force-time curve parameters may be dependent on swimming style, future studies should be conducted for a better understanding of the magnitude of contribution of biomechanical parameters in the performance of swimmers.

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