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Sao Paulo State University
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Unidade – Presidente Prudente

POSTGRADUATE PROGRAM IN MOVEMENT SCIENCES – INTERUNITS

FLÁVIA ALVES DE CARVALHO

INVESTIGATION OF THE FATIGUE AND RECOVERY PROCESS OF SWIMMERS USING PERCEPTIVE, MYOTONOMETRIC, ERGOMETRIC AND BIOMECHANICAL PARAMETERS

Presidente Prudente

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CIÊNCIAS DO MOVIMENTO
PROGRAMA DE PÓS-GRADUAÇÃO

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INVESTIGATION OF THE FATIGUE AND RECOVERY PROCESS OF SWIMMERS USING PERCEPTIVE, MYOTONOMETRIC, ERGOMETRIC AND BIOMECHANICAL PARAMETERS

Thesis presented to the Faculty of Science and Technology of the Sao Paulo State University "Júlio de Mesquita Filho" (FCT/UNESP) – Presidente Prudente, as part of the requirements for obtaining the title of Doctor in the Stricto Sensu Postgraduate Program in Movement Sciences.

Supervisor: Prof. Dr. Carlos Marcelo Pastre

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POTENTIAL IMPACT OF THIS RESEARCH

The products presented in the thesis document entitled *"Investigation of the fatigue and recovery process of swimmers using perceptive, myotonometric, ergometric and biomechanical parameters"* present scientific and economic impacts that promote advances in knowledge in the areas of health and well-being. More specifically, this work impacts the current knowledge in the literature on the concepts of recovery by using a model focused on movement, which has not yet been studied in this context. Research related to this topic has generated great advances in recent years; however, the lack of consensus on the most relevant variables for evaluating athletes in the field impairs its application in practice appropriately. Movement evaluation impacts the understanding of the repercussions of recovery strategies used in the daily lives of athletes and assists the clinical decision-making process of health professionals who work with this population. Moreover, this study shows the applicability of assessment methods and equipment that can be found in swim teams. This represents a more affordable way to monitor athletes' performance and recovery in practice and research without the need for large spaces, swimming pools and water-proof cameras. The study also presents scientific and innovative potential by using technologies for the academic recording of phenomena observed in clinical practice so that they can be studied, helping to promote intervention and prevention strategies in the sports field. In addition, this project had national and international collaboration from leading researchers, enabling the exchange of ideas and the creation of partnerships for future projects that continue to develop new ideas based on the knowledge generated by the results presented in this work.

ATA DA DEFESA PÚBLICA DA TESE DE DOUTORADO DE FLÁVIA ALVES DE CARVALHO, DISCENTE DO PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS DO MOVIMENTO, DA FACULDADE DE CIÊNCIAS E TECNOLOGIA - CÂMPUS DE PRESIDENTE PRUDENTE.

Aos 14 dias do mês de janeiro do ano de 2025, às 8h, por meio de Videoconferência, realizou-se a defesa de TESE DE DOUTORADO de FLÁVIA ALVES DE CARVALHO, intitulada **INVESTIGATION OF THE FATIGUE AND RECOVERY PROCESS OF SWIMMERS USING PERCEPTIVE, MYOTONOMETRIC, ERGGOMETRIC AND BIOMECHANICAL PARAMETERS**. A Comissão Examinadora foi constituída pelos seguintes membros: Prof. Dr. FÁBIO MÍCOLIS DE AZEVEDO (Participação Virtual) do(a) Departamento de Fisioterapia / UNESP - Faculdade de Ciências e Tecnologia de Presidente Prudente - SP, Prof. Dr. SERGIO TEIXEIRA DA FONSECA (Participação Virtual) do(a) Departamento de Fisioterapia / Universidade Federal de Minas Gerais - UFMG, Prof. Dr. ALESSANDRO MOURA ZAGATTO (Participação Virtual) do(a) Departamento de Educação Física / UNESP - Faculdade de Ciências de Bauru - SP, Prof. Dr. LUCIANO SALES PRADO (Participação Virtual) do(a) Departamento de Educação Física / Universidade Federal de Minas Gerais - UFMG, Prof. Dr. RINALDO ROBERTO DE JESUS GUIRRO (Participação Virtual) do(a) Departamento de Biomecânica, Medicina e Reabilitação do Aparelho Locomotor - Ribeirão Preto/SP / Universidade de São Paulo - USP. Após a exposição pela doutoranda e arguição pelos membros da Comissão Examinadora que participaram do ato, de forma presencial e/ou virtual, a discente recebeu o conceito final:_ _ _ _ _ _ _ _ _ _ _ _ _ _ _ APROVADA _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ . Nada mais havendo, foi lavrada a presente ata, que após lida e aprovada, foi assinada pelo(a) Presidente(a) da Comissão Examinadora.

Prof. Dr. FÁBIO MÍCOLIS DE AZEVEDO

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ABSTRACT

The latest consensus on sports science is that performance and recovery decisions should be tailored based on the integrated monitoring of several variables. However, interpretation of this concept is limited because the ideal model is still unknown. Therefore, the investigation of recovery, which is a complex phenomenon, could benefit from assessing a variable that is representative of the whole process and should consider sport specificity. Therefore, in this study we suggest the that movement assessment along with the athlete`s perceptions, muscle properties and performance could add relevant information to the actual scenario. This study was carried out to evaluate the recovery process in swimmers from beginning to end, using massage and immersion in cold-water, which are frequently used techniques in the field. Our main objective was to test a theoretical model using the sporting gesture as a representative variable of the recovery process of swimmers. This study included 22 healthy young swimmers from Brazil which were submitted to procedures divided in three stages. The first stage consisted of investigating the adequacy of the procedures performed by evaluating the tests used. The second stage included evaluating the effects of fatigue on movement and variables that could potentially be influenced by it. Finally, the short-term effect of massage and cold-water immersion (CWI) compared to control immediately after fatigue. The outcomes assessed were training-related perceptions (physical and mental readiness, fatigue, vigor, somnolence and pain), shoulder sense of position, upper limb muscle viscoelastic properties (muscle tone, stiffness and elasticity), ergometric (distance swam pace, stroke frequency, power and count) and biomechanic variables (shoulder and elbow flexion degrees during a simulated stroke cycle). Fatigue was induced during a swim protocol consisting of 8 x 100m freestyle submaximal sprints using palmar and parachutes and assessed during a simulated swim test on swim ergometer using inertial measurement units. Reliability of the tests and tools were assessed using intraclass correlation coefficients and minimal detectable changes. Comparation between the tested conditions was carried out using one-dimensional statistical parametric mapping analogous to repeated measures analysis of variance for time series and using generalized linear models for the remaining variables. We found that ergometric and biomechanical outcomes can be reliably reproduced between training sessions, but perceptive, proprioceptive and muscle parameters have great variability and should be interpreted with caution considering clinically relevant parameters. In addition, fatigue can be consistently tested using simulated swim ergometer and can alter the movement behavior of the shoulder and elbow, possibly impacting swimmers' performance. Finally, in addition to improving swimmers' perceptions, CWI showed a protective effect by mitigating fatigue repercussions in movement variability. Although recovery strategies are usually not recommended on the basis of performance assessments, CWI is shown to impact not only self-reported outcomes but also movement variability. The high adherence to therapeutic techniques for recovery, despite the lack of strong evidence, suggests that the outcomes investigated so far may not reflect the totality of the systems state and future studies on this subject can enrich the theory and practice regarding post-exercise recovery.

Key-words: *Swimming, Sports Massage, Cryotherapy, Movement*

RESUMO

O consenso mais recente na ciência do esporte é que as decisões sobre desempenho e recuperação devem ser personalizadas com base no monitoramento integrado de diversas variáveis. No entanto, a interpretação desse conceito é limitada, pois o modelo ideal ainda é desconhecido. Dessa forma, a investigação da recuperação, que é um fenômeno complexo, pode se beneficiar da avaliação de uma variável representativa de todo o processo e que considere a especificidade do esporte. Neste estudo, sugerimos que a avaliação do movimento, juntamente com as percepções do atleta, as propriedades musculares e o desempenho, pode acrescentar informações relevantes ao cenário atual. Este estudo foi realizado para avaliar o processo de recuperação de nadadores do início ao fim, utilizando massagem e imersão em água fria, que são técnicas frequentemente empregadas na área. Nosso principal objetivo foi testar um modelo teórico utilizando o gesto esportivo como uma variável representativa do processo de recuperação dos nadadores. O estudo incluiu 22 jovens nadadores saudáveis do Brasil, submetidos a procedimentos divididos em três etapas. A primeira etapa consistiu na investigação da adequação dos procedimentos realizados por meio da avaliação dos testes utilizados. A segunda etapa incluiu a avaliação dos efeitos da fadiga sobre o movimento e variáveis que poderiam ser potencialmente influenciadas por ela. Por fim, avaliou-se o efeito de curto prazo da massagem e da imersão em água fria (IAF) em comparação ao controle imediatamente após a fadiga. Os desfechos avaliados foram: percepções relacionadas ao treino (preparo físico e mental, fadiga, vigor, sonolência e dor), senso de posição do ombro, propriedades viscoelásticas dos músculos dos membros superiores (tônus muscular, rigidez e elasticidade), variáveis ergométricas (distância nadada, ritmo, frequência de braçadas, potência e contagem) e variáveis biomecânicas (graus de flexão do ombro e cotovelo durante um ciclo simulado de braçada). A fadiga foi induzida por meio de um protocolo de natação composto por 8 x 100m de sprints submáximos no estilo livre, utilizando palmares e paraquedas, e avaliada durante um teste de nado simulado em um ergômetro de natação com uso de unidades de medição inercial. A confiabilidade dos testes e ferramentas foi avaliada por meio dos coeficientes de correlação intraclasse e das menores mudanças detectáveis. A comparação entre as condições testadas foi realizada utilizando mapeamento estatístico paramétrico unidimensional, análogo à análise de variância para medidas repetidas em séries temporais, e modelos lineares generalizados para as demais variáveis. Identificamos que os desfechos ergométricos e biomecânicos podem ser reproduzidos de maneira confiável entre as sessões de treino, mas os parâmetros perceptivos, proprioceptivos e musculares apresentam grande variabilidade e devem ser interpretados com cautela, considerando parâmetros clinicamente relevantes. Além disso, a fadiga pode ser testada de forma consistente utilizando um ergômetro de natação simulado e pode alterar o comportamento do movimento do ombro e do cotovelo, possivelmente impactando o desempenho dos nadadores. Por fim, além de melhorar as percepções dos nadadores, a IAF demonstrou um efeito protetor, atenuando as repercussões da fadiga na variabilidade do movimento. Embora as estratégias de recuperação geralmente não sejam recomendadas com base em avaliações de desempenho, a IAF demonstrou impactar não apenas os desfechos autorrelatados, mas também a variabilidade do movimento. A alta adesão às técnicas terapêuticas de recuperação, apesar da falta de evidências robustas, sugere que os desfechos investigados até o momento podem não refletir a totalidade do estado dos sistemas. Estudos futuros sobre esse tema podem enriquecer a teoria e a prática relacionadas à recuperação pós-exercício.

Palavras-chave: Natação, Massagem esportiva, Crioterapia, Movimento

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LIST OF ABBREVIATIONS AND SYMBOLS

AIC	Akaike Corrected Criterion
BB	Biceps Brachii
BMI	Body Mass Index
CON	Control
CONSORT	Consolidated Standards of Reporting Trials
CWI	Cold-water immersion
FAT	Fatigue protocol
ICC	Intraclass Correlation Coefficient
IMU	Inertial Measurement Units
LD	Latissimus dorsi
MAS	Massage
MD	Middle Deltoid
MDC	Minimal Detectable Change
PM	Pectoralis Major
RAD	Resulting angular deviation
SEM	Standard Error of Measurement
SD	Standard Deviation
SPIRIT	Standard Protocol Items: Recommendations for International Trials
SPM1D	One-dimensional Statistical Parametric Mapping
SPSS	Statistical Package for the Social Sciences
STROBE	Strengthening the reporting of observational studies in epidemiology
TB	Triceps Brachii
UT	Upper Trapezius
VC	Variability Coefficient

SUMMARY

PRESENTATION AND STATEMENT OF THE RESEARCH PROBLEM

This thesis is presented in accordance with the Scandinavian model proposed by the Stricto Sensu Postgraduate Program in Physiotherapy of the Faculty of Science and Technology of the São Paulo State University "Júlio de Mesquita Filho" in accordance with INSTRUCTION No. 14/2023/PPGCMI.

The content of this work includes the material originated from the research entitled *"Investigation of the fatigue and recovery process of swimmers using perceptive, myotonometric, ergometric and biomechanical parameters"*. The assessment of recovery is still a challenge for researchers and clinicians due to its multifactorial and complex nature. In this context, findings from studies using different models for recovery can be confusing and limit interpretation and clinical application. Therefore, there is a need to explore ways to synthesize the information to guide field intervention. Considering the complexity of human behavior, it is pertinent to study the recovery process from the point of view of dynamic systems. This research field understands that complex systems may be studied by means of high order parameters which can represent the system without analyzing all its parts. In addition, the analysis of variability in different contexts has shown promising results to understand biological phenomena. In this sense, analyzing movement variability represents a novel strategy to understand the recovery process. However, since these methods have not been previously tested it is also important to understand its reproducibility, the impacts of fatigue on the sports movement, and finally the impact of recovery on this outcome. Furthermore, variables from different dimensions might be needed to explain the results.

To answer these research questions, this study was carried out to evaluate the recovery process in swimmers from beginning to end, using massage and immersion in cold-water, which are frequently used techniques in the field. Our main objective was to test a theoretical model using the sporting gesture as a representative variable of the recovery process of swimmers. To evaluate recovery in an ecological context, it is important to incorporate phenomena observed in practice. Therefore, the present study proposed to investigate the fatigue of swimmers using a protocol carried out in a pool and to assess variables that could be influenced by the tested interventions. To this end, the investigation was carried out in three stages. The first stage consisted of investigating the adequacy of the procedures performed by evaluating the tests used. The second stage included evaluating the effects of fatigue on movement and variables that could potentially be influenced by it. Finally, the short-term effect of these techniques was tested immediately after fatigue. Therefore, this research generated four scientific products described below and presented separately in the

form of chapters containing the manuscripts formatted according to the guidelines of the journals chosen for submission, in English.

The first product refers to the detailed research protocol following the Standard Protocol Items: Recommendations for International Trials (SPIRIT) guidelines. The publication of this study not only ensures transparency in the process but also allows for the description of all processes in an adequate manner so that they can be adequately evaluated and reproduced. Next, the results of the test-retest investigation of the instruments and procedures used in the study are presented. This stage is relevant since, unlike other conditions tested in the literature, it is impossible to isolate the effects of the training in which the athletes are inserted during repeated evaluations, which can generate large fluctuations in the monitored variables. The results of this study allow us to obtain values for the interpretation of clinically relevant changes in the context of swimmer training. The third product presented consists of the investigation of the suitability of a simulated swimming test to assess the repercussions of fatigue performed in the water in relation to the variables used during the study. In simple terms, the study aimed to investigate whether the results found could be applied in some way in clinical practice. Finally, the fourth product refers to the clinical trial conducted to investigate the effects of the techniques investigated on the variables already mentioned and the preferences of athletes regarding the use of these techniques on the execution of the sporting gesture and their perceptions.

At the end of the text are presented the activities developed by the candidate during the doctoral course.

CHAPTER FIVE:
Final considerations

This thesis contains the results from different manuscripts that, together, add relevant information to the literature regarding swimmers' monitoring and the assessment of the recovery process. The first manuscript details the procedures used throughout the project execution. This is of special relevance regarding the movement assessment which has not been used so far in this context.

The second product provides information on the reliability of tests and tools that comprehend different aspects of the swimmers' demands. Results show that ergometric and biomechanical variables can be reproduced in different days within the similar training conditions, but muscle assessments and training-related perceptions are highly variable. Therefore, decision making should consider possible interactions from these variables, and the values of minimal detectable changes can be used to aid interpretation of future studies on this matter.

The third product describes the effects of two fatigue protocols in swimmers. Although they are essentially different regarding physiological demands, we aimed to understand if the outcomes used in this protocol could be reproduced during a simulated swim protocol allowing the investigation of fatigue and recovery. We found that although frequently reported by the swimmers after fatigue, muscle tone and stiffness measured by myotonometry does not change after both tested protocols, and self-reported perceptions were found to be similar between the two protocols. In addition, we were able to register changes in the movement behavior of the shoulder and elbow which are frequently observed in practice. The findings regarding movement variability show that there is more to explore, and that using other methods within the dynamic systems field could provide insights from a new perspective in sports sciences.

Finally, the fourth product shows the effects of two of the most used recovery strategies on these variables. The results from the previous studies provide the basis for interpretation and ensure internal validity of the testing protocol. We found that CWI can have meaningful impacts on the athletes' fatigue compared to massage and may have implications for movement variability. Self-similarity analysis can provide information on the system behavior and its relation to recovery and give better clinical explanations for these findings. Moreover, although the exercise may not have altered the state of

muscle properties CWI can significantly impact some muscles due to shivering, which reinforces the necessity of rewarming prior to exercise.

Together, these results show that, although recovery strategies are usually not recommended on the basis of performance assessments, they may have impacts not only on self-reported outcomes but also on the quality of movement, especially CWI. The high adherence to therapeutic techniques for recovery, despite the lack of strong evidence, suggests that the outcomes investigated so far may only scratch the surface of this complex phenomena and not reflect the totality of the systems state. Our results suggest that there is a whole new field to be explored to investigate athletic recovery which can enrich the literature with future studies, such as the relationship of movement variability with other measurable outcomes, and the exploration of the role of system complexity on fatigue and recovery.

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