UNIVERSIDADE DA BEIRA INTERIOR
Ciências Sociais e Humanas

The effects of warming up strategies for sprint performance: emerging approaches

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Tese para obtenção do Grau de Doutor em
Ciências do Desporto
(3º ciclo de estudos)

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Covilhã, dezembro de 2019

The stars that shine in the sky, shine in my heart and illuminate my way...
To my grandmothers Rosária Gil e Deolinda Gonçalves and my great friend Danny Costa.

Academic thesis submitted with the purpose of obtaining a doctoral degree in Sport Sciences according to the provisions of Portuguese Decree-Law 107/2008 of 25 June.

Acknowledgments

Gratitude is the act of recognizing the importance of a person in our lives. Thus, I would like to express my deep gratitude to those who contributed in some extent for conclusion of my doctoral thesis.

Thanks to Professor *Daniel Almeida Marinho* and Professor *Henrique Pereira Neiva* for their supervision, guidance, counseling and all the support. Thank you for your exceptional knowledge, patience and friendship all these years…thanks for all the support and for not letting me give up every time my world collapsed.

Thanks to Professor *Mário António Cardoso Marques*, I am highly thankful by contributing with his knowledge and vast years of experience, friendship and incredible support of this thesis. Thank you to the master of the masters ... the mentor who taught me to do science.

One special thank to my parents *Fernanda Maria Gonçalves Rafael Gil* and *Antório Gabriel da Silva Gil*. They went my bigger support...they gave me forces and they went my shelter in stormy days. They are my reason to live.

Thanks to my boyfriend, *António Carlos Bettencourt Sousa*, for all the companionship and support during these 11 years.

Thanks to Professor *Pedro Alexandre Duarte Mendes* for the total availability in collaboration of the study carried out at the Polytechnic Institute of Castelo Branco, as well as in the solution of problems and doubts that have arisen during the accomplishment of this investigation.

Thanks to Professor *Mário António Cardoso Marques*, Professor *Pedro Alexandre Duarte Mendes*, Professor *Nuno Domingos Garrido Nunes de Sousa*, Professor *Ricardo Manuel Pires Ferraz*, Professor *Maria do Socorro Cirilo-Sousa*, and to my Friend *Ana Sofia Alves*, co-authors and collaborators in our research project. Thank you for your constant encouragement, dedication, and essential aid.

Thanks to all collaborators in data collection of our research, *Adenilson Júnior, Hidayane Gonçalves, Gabriel Rodrigues Neto, Simoni Bittar*, *Patrick Pfeiffer, André Ramalho, Luís Faíl, Diogo Marques, Diogo Pinto, Ana Alves, Tiago Lopes, Carlota Gonçalves, Claúdia Graça, António Sousa*, Professor *Daniel Marinho*, Professor *Henrique Neiva*, Professor *Pedro Mendes*, Professor *Nuno Garrido* and Professor *Ricardo Ferraz*.

Thanks to students of University of Beira Interior, of Polytechnic Institute of Castelo Branco, and of Federal University of Paraíba for your interest, dedication and contribution in this research project.

Thanks to D. *Vera Batista,* a second mother in department of sport sciences.

Thanks to my friends and my second family, *Pedro Miguel Pombo Neves*, *Luís Oliveira Brandão Faíl*, *Rui Pedro Carriço Cabral*, *Diogo Ferreira Pinto*, and *Maressa Paschoalleto Daroz*...the family that Covilhã give me.

Thanks to my best friends *Dineia Almeida Lucas*, *Pedro Miguel Pombo Neves* and *Luís Oliveira Brandão Faíl* for all the moments of encouragement. Thank you for always being present when I needed it most.

The last but not the least, to all my family for the constant support.

List of Publications

This Doctoral Thesis is supported by the following papers:

- **Gil, M.H.**, Neiva, H.P., Sousa, A.C., Marques, M.C. & Marinho, D.A. (2019). Current approaches on warming up for sports performance: a critical review. *Strength and Conditioning Journal, 41*(4), 70–79.

- **Gil, M.H.**, Neiva, H.P., Garrido, N.D., Aidar, F.J., Cirilo-Sousa, M.S., Marques, M.C., & Marinho, D.A. (2019). The effect of ballistic exercise as pre-activation for 100m sprints. *International Journal of Environmental Reasearch and Public Health, 16*(10), 1850.

- **Gil, M.H.**, Neiva, H.P., Alves, A.R., Sousa, A.C., Mendes, P.D., Marques, M.C., & Marinho, D.A. (2019). Does the inclusion of ballistic exercises during warm-up enhance short distance running performance? *The Journal of Sports Medicine and Physical Fitness (in press).*

- **Gil, M.H.**, Neiva, H.P., Alves, A.R., Sousa, A.C., Ferraz, R., Marques, M.C., & Marinho, D.A. (2019). The effect of warm-up running technique on sprint performance. *Submitted for publication to Journal of Strength and Conditioning Research.*

Beyond these papers, some preliminary studies were conducted as a preliminary approach to warm-up issue:

- Marinho, D.A., **Gil, M.H.**, Marques, M.C., Barbosa, T.M., &Neiva, H.P. (2017). Complementing warm-up with stretching routines: effects in sprint performance. *Sports Medicine International Open, 1*(3), E101-106. doi: 10.1055/s-0043-111788.

- Morouço, P.G., **Gil, M.H.**, Neiva, H.P., Marques, M.C., Sousa, A., & Marinho, D.A. (2017). *The effect of warm-up on sprinting kinematics.* In: W. Potthast, A. Niehoff, & S. David (eds.), 35th International Conference on Biomechanics in Sports (pp. 440-443). Cologne, Germany: International Society of Biomechanics in Sports.

- **Gil, M.H.**, Marques, M.C., Neiva, H.P., Mendes, P.A., Sousa, A.C., Alves, A.S., Branquinho, L., Faíl, L.O., Pinto, D., Marques, D., Graça, C., Marinho, D.A. (2017). *Correlations between biomechanical variables and sprint time of 30m.* In: N. Serra,

C. Vila-Chã, N. Casanova, P. Esteves, & M. Costa (Eds), Livro de Abstracts – XIII SIEFLAS Seminário Internacional de Educação Física, Lazer e Saúde, (p.118). Guarda: Instituto Politécnico da Guarda.

- **Gil, M.H.**, Marques, M.C., Neiva, H.P., Sousa, A.C., & Marinho, D.A. (2017). External heating garments used post-warm-up and effects in sports performance. *BMC Sports Science, Medicine and Rehabilitation, 9*(Suppl 1), 3, A10.

Abstract

In recent years, the benefits of warm-up in sports performance have received a special interest. New methods have been included in warm-up procedure, but few are known about the effects on running performance and biomechanical responses. Thus, the purpose of the current thesis was to analyze the effect of recent trends of warm-up tasks on sprint performance. Specifically, to verify the effects of including ballistic exercises in warm-up procedures and to analyze the impact of changing biomechanical running patterns during warm-up, conducting a performance, biomechanical, physiological and psychophysiological evaluation of sprints. For this, the following steps were performed: (i) qualitative review on warm-up and performance, focusing on the emerging methods; (ii) to verify the acute effects of a warm-up including ballistic exercises inducing a post-activation potentiation, easy to apply on a real competition context, in repeated 100m running performance; (iii) to understand the acute physiological, psychophysiological and biomechanical responses of including ballistic exercises in repeated 30m running performance; (iv) to analyze the effect of manipulating running kinematics (stride length (SL) and stride frequency (SF)) during warm-up in repeated 30m running performance. The main conclusions of the study were: (i) considering the new trends that have emerged, it can be suggested positive effects on performance after short duration stretches followed by specific muscle activation exercises, and after dynamic stretching, both depending on the duration and intensity; short-duration maximal efforts and specific to the following activity, followed by few minutes of recovery, provide beneficial neuromuscular responses and improved performance in high-intensity and short-term efforts; passive heating during the transition phase between warm-up and main exercise lead to optimization of subsequent performance; (ii) there were benefitial effects of warm-up in 30m and 100m sprinting; (iii) the 100m race is equally optimized after warm-up with or without post-activation potentiation, but with different running kinematics (iv) the positive effects of warm-up on 30m running was caused by faster initial 15m and increased SL in the last 15m of the trial; v) no additional effects on 30m were found after including ballistic exercises during warm-up; (vi) a warm-up focusing in higher SL or higher SF did not result in different 30m sprint performances and running kinematics, despite different running strategies occurred (faster initial meters after warm-ups stimulating SF and faster final meters after warm-up stimulating SL); (vii) the results highlighted the individual response to each warm-up procedure. The main findings of this work emphasize the importance of the warm-up design for short running distances and the need of individualization for optimized performances. Further studies are needed to deeply understand their effects on performance.

Key-words

Warm-up; Performance; Repeated sprint; Physiology; Biomechanics

Resumo

Nos últimos anos, os benefícios do aquecimento no desempenho desportivo receberam um interesse especial. Novos métodos foram incluídos no processo de aquecimento, mas pouco se conhece sobre os seus efeitos no desempenho de corrida e respostas biomecânicas. Assim, o objetivo a presente tese foi analisar o efeito das tendências recentes de tarefas de aquecimento no desempenho do sprint. Especificamente, verificar os efeitos da inclusão de exercícios balísticos nos procedimentos de aquecimento e analisar o impacto da mudança dos padrões biomecânicos de corrida durante o aquecimento, conduzindo a uma avaliação de performance, biomecânica, fisiológica e psicofisiológica dos sprints. Para isso, foram realizadas as seguintes etapas: (i) revisão qualitativa do aquecimento e desempenho, com foco nos métodos emergentes; (ii) verificar os efeitos agudos de um aquecimento, incluindo exercícios balísticos que induzem uma potenciação pós-ativação, fácil de aplicar em contexto real de competição, no desempenho de corrida repetida de 100m; (iii) compreender as respostas fisiológicas agudas, psicofisiológicas e biomecânicas com a inclusão de exercícios balísticos no desempenho de 30m de sprint repetido; (iv) analisar o efeito da manipulação da cinemática de corrida (comprimento da passada (CP) e frequência da passada (FP)) durante o aquecimento em performances de sprint repetido de 30m. As principais conclusões do estudo foram: (i) considerando as novas tendências que surgiram, pode-se sugerir efeitos positivos no desempenho após alongamentos curtos seguidos de exercícios específicos de ativação muscular, e após alongamento dinâmico, ambos dependendo da duração e intensidade; esforços máximos de curta duração e específicos para a atividade seguinte, seguidos por poucos minutos de recuperação, fornecem respostas neuromusculares benéficas e melhor desempenho em esforços de alta intensidade e de curto prazo; o aquecimento passivo durante a fase de transição entre o aquecimento e a tarefa principal leva à otimização do desempenho subsequente; (ii) houve efeitos benéficos do aquecimento no sprint de 30m e 100m; (iii) a corrida de 100m é igualmente otimizada após o aquecimento com ou sem potenciação pós-ativação, mas com cinemática de corrida diferente; (iv) os efeitos positivos do aquecimento nos 30m de corrida foram causados por 15m iniciais mais rápidos e maior CP nos últimos 15m de prova; (v) não foram encontrados efeitos adicionais nos 30m após a inclusão de exercícios balísiticos durante o aquecimento; (vi) um aquecimento focado em maior CP ou maior FP não resultou em diferenças no desempenho e cinemática nos 30m sprint, apesar de terem ocorrido diferentes estratégias de corrida (fase inicial mais rápida após aquecimento estilmulando FP e fase final mais rápida após aquecimento estimulando CP); (viii) os resultados destacaram a resposta individual a cada procedimento de aquecimento. As principais conclusões deste trabalho enfatizam a importância do desenho do aquecimento para distâncias curtas e a necessidade de individualização para desempenhos otimizados. Outros estudos são necessários para entender profundamente seus efeitos sobre o desempenho.

Palavras-chave

Aquecimento; Desempenho; Sprint Repetido; Fisiologia, Biomecânica

Resumen

En los últimos años, los beneficios de la calefacción en el rendimiento deportivo recibieron un interés especial. Nuevos métodos se incluyeron en el proceso de calentamiento, pero poco se conoce sobre sus efectos en el rendimiento de la carrera y las respuestas biomecánicas. Así, el objetivo de la presente tesis fue analizar el efecto de las tendencias recientes de tareas de calentamiento en el desempeño del sprint. Específicamente, verificar los efectos de la inclusión de ejercicios balísticos en los procedimientos de calentamiento y analizar el impacto del cambio de los patrones biomecánicos de carrera durante el calentamiento, conduciendo a una evaluación de desempeño, biomecánica, fisiológica y psicofisiológica de los sprints. Para ello, se realizaron las siguientes etapas: (i) revisión cualitativa del calentamiento y desempeño, con foco en los métodos emergentes; (ii) verificar los efectos agudos de un calentamiento, incluyendo ejercicios balísticos que inducen una potenciación post-activación, fácil de aplicar en contexto real de competición, en el desempeño de carrera repetida de 100m; (iii) comprender las respuestas fisiológicas agudas, psicofisiológicas y biomecánicas con la inclusión de ejercicios balísticos en el desempeño de 30m de sprint repetido; (iv) analizar el efecto de la manipulación de la cinemática de carrera (longitud de la pasada (LP) y frecuencia de la pasada (FP)) durante el calentamiento en performances de carrera repetida de 30m. Las principales conclusiones del estudio fueron: (i) considerando las nuevas tendencias que surgieron, se pueden sugerir efectos positivos en el desempeño después de estiramientos cortos seguidos de ejercicios específicos de activación muscular, y después del estiramiento dinámico, ambos dependiendo de la duración e intensidad; los esfuerzos máximos de corta duración y específicos para la actividad siguiente, seguidos por pocos minutos de recuperación, proporcionan respuestas neuromusculares benéficas y un mejor desempeño en esfuerzos de alta intensidad y de corto plazo; el calentamiento pasivo durante la fase de transición entre el calentamiento y la tarea principal lleva a la optimización del rendimiento posterior; (ii) hubo efectos beneficiosos de la calefacción en el carrera de 30m y 100m; (iii) la carrera de 100m es igualmente optimizada después del calentamiento con o sin potenciación post-activación, pero con cinemática de carrera diferente; (iv) los efectos positivos del calentamiento en los 30m de carrera fueron causados por 15m iniciales más rápidos y mayor LP en los últimos 15m de prueba; (v) no se encontraron efectos adicionales a los 30 metros tras la inclusión de ejercicios balísticos durante la calefacción; (vi) un calentamiento enfocado en mayor LP o mayor FP no resultó en diferencias en el rendimiento y cinemática en los 30m sprint, a pesar de haber ocurrido diferentes estrategias de carrera (fase inicial más rápida después de calentamiento estilmulando FP y fase final más rápida después de calentamiento estimulando LP); (viii) los resultados destacaron la respuesta individual a cada procedimiento de calentamiento. Las principales conclusiones de este trabajo enfatizan la importancia del diseño del calentamiento para distancias cortas y la necesidad de individualización para desempeños optimizados. Otros estudios son necesarios para entender profundamente sus efectos sobre el rendimiento.

Palabras-clave

Calefacción; Rendimiento; Sprint Repetido; Fisiología; Biomecánica.

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Appendix I

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List of Abbreviations

ANOVA	Analysis of variance
Bpm	Beats per minute
^{o}C	Celsius
CI	Confidence interval
DS	Dynamic stretching
ES	Effect size
HR	Heart rate
Hz	Hertz
$[La^-]$	Blood lactate concentration
M	Meters
Min	Minute
NWU	No warm-up
PAP	Post-activation potentiation
PNF	Proprioceptive neuromuscular facilitation
1RM	One-repetition maximum
RPE	Ratings of perceived exertion
SD	Standard deviation
SF	Stride frequency
SL	Stride length
SS	Static stretching
Tc	Core temperature
Tm	Muscle temperature
Tymp T	Tympanic temperature
T0-15	Sprint time of 0m to 15m
T0-50	Sprint time of 0m to 50m
T15-30	Sprint time of 15m to 30m
T30	Sprint time of 30m
T50-100	Sprint time of 50m to 100m
T100	Sprint time of 100m
VO_2max	Maximum oxygen uptake
WU	Typical warm-up
WUF	Warm-up stimuling stride frequency
WUL	Warm-up stimuling stride length
η_p^2	partial eta squared

Chapter 1. General Introduction

Warming-up before training or competition has become one of the most interesting topics, evidenced by the number of recent publications (e.g. McGowan, Pyne & Thompson, 2015; Neiva, Marques, Barbosa, Izquierdo & Marinho, 2014; Silva, Neiva, Marques, Izquierdo & Marinho, 2018). Researchers, coaches and athletes are aware of the importance of the warm-up practices and the deepening of the knowledge on this subject is understood as essential to optimize performance and to prevent injuries (McGowan et al., 2015; Neiva et al., 2014; Silva et al., 2018). The warm-up is usually intended to generate muscle and body temperature increase that allows several internal changes (Bishop, 2003a, Bishop, 2003b). For instance, it was reported a decrease in time to achieve peak tension and relaxation (Segal, Faulkner & White, 1986), a reduction of viscous resistance of the muscles and joints and increased muscle blood flow (Pearson *et al.*, 2011), most likely resulting in optimized aerobic function, improved efficiency of muscle glycolysis and high-energy phosphate degradation during exercise (Febbraio, Carey, Snow, Stathis & Hargreaves, 1996; Gray & Nimmo, 2001; Pearson *et al.*, 2011) and increased nerve conduction rate (Karvonen, 1992).

The increase in body temperature can be achieved by using physical activity (active warm-up) or using external means without performance of any kind of physical activity (passive warm-up (Bishop, 2003a, Bishop, 2003b). It was reported that, in addition to the increased body temperature, other effects exist when the participants perform active warm-up, such as increased resting oxygen uptake, a post-activation potentiation (PAP) effect influenced by the previous activity of the same muscle group, and psychological effects (McGowan et al., 2015; Silva et al., 2018). Thus, this is the most commonly used method before training and competition (Neiva et al., 2014). Nevertheless, passive procedures have been recently reported as a reliable alternative to active strategy, in order to allow the increased temperature obtained during the warm-up to be maintained (McGowan et al., 2017).

Research on the use of warm-up techniques has shown benefits for performance in cycling (Burnley, Doust & Jones, 2005), running (Marinho, Gil, Marques, Barbosa & Neiva, 2017; Zois, Bishop, Ball & Aughey, 2011) or even specific activities as the vertical jump (Burkett, Phillips & Ziuraitis, 2005). However, in other similar activities the performances are impaired (Bradley, Olsen & Portas, 2007; Di Cagno et al., 2010; Tomaras & MacIntosh, 2011). This could happen due to the different warm-up designs used and reveal the importance of knowing better how it should be structured. There is a need for understanding how to combine the different variables of warm-up, as the volume, the intensity, the tasks to be performed, the environmental conditions and the specific constrains of training and competition (Fradkin, Zaryn & Smoliga, 2010; Silva et al., 2018; Tillin & Bishop, 2009). In this sense, the effectiveness of the warm-up before maximal efforts (Burnley et al., 2005; Gray & Nimmo, 2013, Neiva et al., 2014), and the effect of the use of different volumes, intensities and recovery periods (Kilduff et al., 2008; Mitchell & Huston, 1993; Neiva et al., 2015) only lately have been studied.

It was found that an excess of volume during warm-up might impair the subsequent performance (Neiva et al., 2015; Tomaras & MacIntosh, 2011). Also, it was shown that different warm-up intensities could led to identical results, but with different physiological and mechanical adaptations (Mitchell & Huston, 1993; Neiva et al., 2017). Yet, it took only 20min to physiological responses return to baseline level (West et al., 2013). It seems of interest to extend the effects of warm-up, not only using effective exercises but also finding ways of optimizing the waiting time before the physical activity to start. Different tasks have been applied recently by coaches and researchers and new trends in research have therefore emerged. One should know and understand what recent research have evidenced regarding these new practices such as the use of different warm-ups combined with several stretching strategies, tasks focused on PAP, and passive warm-up strategies to allow maintaining the increased temperature obtained during warm-up (Barbosa, Barroso & Andries, 2016; McGowan, Thompson, Pyne, Raglin & Rattray, 2016; Russel et al., 2015).

There is a wide range of warm-up procedures that can be combined and used by coaches and athletes, but further evidence from controlled studies is needed to demonstrate their efficiency. For instance, in running, despite it is well stablished that warm-up improve sprint performance (Silva et al., 2018; Zois et al., 2011), there is a lack of information about the effects of different warm-up tasks in sprint performance. Usually, a warm-up includes a brief period of low intensity aerobic followed by specific exercises focusing on the following activity (Andrade et al., 2015; Silva et al., 2018). During the specific warm-up, coaches have been including dynamic and static stretching, agility exercises, and PAP activities (Kallerud & Gleeson, 2013; Perrier, Pavol & Hoffman, 2011). These last, the PAP related activities, are a recent trend of specific warm-up and are believed to enhance subsequent performance (Borba, Ferreira-Júnior, Santos, Carmo & Coelho, 2017; Hancock, Sparks & Kullman, 2015). It seems to augment the muscle’s force-generating capacity (i.e. muscle twitch and low-frequency tetanic force) as a result of the previous contractile history of the muscle cells involved in the previous contraction (Hodgson, Docherty & Robbins, 2005). The PAP phenomenon has been therefore defined as an increase in force production after a maximum or near maximal muscle stimulation (Kallerud & Gleeson, 2013).

Investigation reported improvements between 2 and 3% in 10m, 30m and 40m sprints after performing squats at 85% to 90% of one-repetition maximum (1RM) (Rahimi, 2007; Chatzopoulos et al., 2007). However, previous research mainly focused on high external loads of strength exercise to stimulate any PAP effects and this is hard to be applied in a real competition context (Gil, Neiva, Sousa, Marques & Marinho, 2019; Kilduff, Owen, Bevan, Bennett & Kingsley, 2008; Rahimi, 2007). As alternative, ballistic exercises have been recently studied. These are a recent trend of specific warm-up and are believed to cause a

PAP phenomenon, thus enhancing the performance (Blagrove, Holding, Patterson, Howatson & Hayes, 2019; Gil et al., 2019). The inclusion of depth jumps in the warm-up was suggested to increase both maximal strength (Masamoto, Larsen, Gates & Faigenbaum, 2003) and vertical jump (Hilfiker, Hubner, Lorenz & Marti, 2007; Stieg et al., 2011). Specifically, in running, some repetitions of depth jumps resulted in 5% additional improvement on 20m sprints performances. However, research is not consensual and the results still not clear on the benefits of including these practices in a typical warm-up. Moreover, little is known about these effects on the biomechanical variables during running (study 2 and study 3). Running performance depends on the optimal ratio between stride length (SL) and stride frequency (SF) enable maximal sprinting velocity (Krzysztof & Mero, 2013). These biomechanical variables can be conditioned by the neuromuscular regulation of movement, morphological characteristics, motor abilities and energy substrates (Coh, Milanovic & Kampmiller, 2001; Prampero et al., 2005), and can be influenced by warm-up tasks (Gil et al., 2019; Neiva et al., 2014; Silva et al., 2018).

Since early, literature has been linking the warm-up benefits to changes in the physiological status of the athletes. However, recently it has been emerging a possibility for the warm-up to cause different important changes, specifically in the sensorimotor activity and conseguently causing motor changes during physical activity (Ajemian, D'Ausilio, Moorman & Bizzi, 2010). Considering that the humans have a high learning ability of the sensorimotor activity, Ajemian et al. (2010) suggested that the warm-up allows some changes in motor learning and thus changing the motor pattern of the athlete, perhaps changing the technical pattern of the sport gesture. This was later corroborated by Neiva et al. (2017) that verified an acute response of freestyle swimming technical pattern according to the specific exercise focusing on higher stroke length or stroke frequency during warm-up. The swimmers replicated the motor skills focused on warm-up during the initial meters of the race. This could justify the importance of the warm-up specificity and the different biomechanical patterns changes caused by warm-up tasks. Knowing that running performance depends on the SL ad SF and these biomechanical variables are mainly conditioned by the neuromuscular regulation of the movement (Coh et al., 2001; Prampero et al., 2005), it would be interesting to find if it can be influenced by specific technical changes during the warm-up tasks. To the best of our knowledge, this was never assessed in running. Most studies in running focused on performance and physiological variables without the full understanding of the warm-up effects. There is a scarcity of knowledge about the effect of warm-up on the biomechanical variables of running, and that could be critical to training and performance (study 4).

Considering the above mentioned, the main purpose of this thesis was to analyze the effect of recent trends of warm-up tasks on sprint performance. Specifically, it was our aims to verify the effects of including ballistic exercises in warm-up procedures and to analyze the impact of changing biomechanical running patterns during warm-up tasks, conducting a performance, biomechanical, physiological and psychophysiological evaluation of sprints.

The thesis is developed according to the following sequence:

- Chapter 2 presents a qualitative review based on the early studies regarding the warm-up and performance, highlighting the newly emerging methods of active and passive warm-ups used before any competitive event to maximize performance (Study 1).

- Chapter 3 shows the experimental studies developed to accomplish the main aim of this thesis:
    - Study 2 aims to verify the acute effects of a warm-up including ballistic exercises inducing a PAP, easy to apply on a real competition context, in 100m running performance. Moreover, a second 100m trial was assessed to better understand the warm-up effects during competition and training.
    - Study 3 was developed to further understand the acute physiological, psychophysiological and biomechanical responses of including ballistic exercises in repeated 30m running performance.
    - Study 4 intended to analyze the effect of manipulating running kinematics (SL and SF) during warm-up in repeated 30m running performance, trying to understand motor learning and biomechanical responses to warm-up specific exercises.

After the studies presentation, a general discussion of the results is provided (Chapter 4), followed by the main conclusions (Chapter 5) and some suggestions for future research (Chapter 6). Some previous studies were developed to better understand the main procedures and some resulting abstracts and manuscripts are presented in appendix.

Chapter 2. Literature review

Study 1

Current approaches on warming up for sports performance: a critical review

Abstract

Warm-up procedures have become relevant for coaches, researchers and sports professionals in recent years. Several studies have been conducted to verify the effects of different pre-activities, regarding differing volume, intensity, rest, and specificity, and the warm-up is now widely accepted as essential practice to improve performance. Research is now focusing on the effects of static and dynamic stretches, the post-activation potentiation phenomenon and the optimisation of waiting periods with passive warm-up approaches. In this brief review we critically analyse the emerging methods and strategies of warm-up that have been investigated and used before competitive events.

Key-Words*:* Competition; Pre-exercise; Heating; Training; Sports performance

Introduction

Before a competitive or training event, athletes usually engage in various activities to increase preparedness and optimize performance, usually called as warm-up (McGowan, Pyne, Thompson & Rattray, 2015). According to Swanson (2006) the purpose of a warm-up is to prepare the athlete for the requirements of training and/or competition. It is believed that a well-designed warm-up causes physiological changes and helps the athlete to increase their mental focus on the next task, allowing them to optimise their performance (McGowan et al., 2015; Neiva et al., 2015).

Warm-up techniques can be broadly classified into two major categories, passive or active (Bishop, Bonetti & Dawson, 2001). Passive warm-up involves raising muscle temperature (Tm) or core temperature (Tc) by some means (e.g. showers or baths, saunas, diathermy, heating pads). Active warm-up involves exercise and is likely to induce greater metabolic and cardiovascular changes than passive warm-up (e.g. jogging, calisthenics, cycling). An active warm-up, involving physical exertion, is the preferred and most commonly used method in almost all athletic events, with some studies reporting additional effects beyond increased temperature. Priming physical activities might stimulate buffering capacity, maintaining the acid-base balance of the body (Beedle & Mann, 2007; Mandengue et al., 2005) and perhaps increasing the baseline of oxygen uptake at the start of subsequent practice, which potentiates the aerobic system (Burnley, Davison & Baker, 2011). Studies have also found increased motor neuron excitability (Saez Saez de Villarreal, González-Badillo & Izquierdo, 2007) and reduced muscle stiffness (Proske, Morgan & Gregory, 1993), allowing easier and more efficient action. Nevertheless, passive strategies have recently been studied as a reliable alternative to active procedures, allowing the increased temperature obtained during warm-up to be maintained (Kilduff, West, Williams & Cook, 2014; McGowan et al., 2017; West et al., 2013).

More than 80% of the published research has shown the positive effects of warm-up on physical performance (Fradkin, Zazryn & Smoliga, 2010), although the impact depends on the intensity and duration of the competition and on the time lag between the warm-up and the competitive event (Neiva, Marques, Barbosa, Izquierdo & Marinho, 2014; Neiva et al., 2016; Zochowski, Johnson & Sleivert, 2007). Warm-up practices have been extensively studied over the last few decades (Bishop et al., 2001; Neiva et al., 2014; Neiva et al., 2015). These practices in individual or team sports usually included a brief period of submaximal aerobic activity (e.g. submaximal run), followed by specific tasks and/or stretching (McGowan et al., 2015; Young, 2007; Zois, Bishop, Ball & Aughey, 2011). While the first is performed at low intensity, the subsequent specific exercise could be performed at higher intensity (e.g. race-pace) to prepare for a competitive event (McMillian, Moore, Hatler & Taylor, 2006; Needham, Morse & Degens, 2009). It may also include dynamic stretching and/or static stretching to reduce muscle stiffness and increase range of motion (Knudson, Bennett, Corn, Leick & Smith, 2001; Yamaguchi & Ishii, 2005), agility exercises and plyometrics to potentiate in force production (Masamoto, Larsen, Gates & Faigenbaum, 2003; Mohr, Krustrup, Nybo, Nielsen & Bangsbo, 2004), as well as the use of thermal-specific clothing to increase or maintain temperature to optimise performance (Abad, Prado, Ugrinowitsch, Tricoli & Barroso, 2011; Lovell, Midgley, Barrett, Carter & Small, 2013). There is thus a wide range of warm-up procedures that can be combined and used by coaches and athletes, but further evidence from controlled studies is needed to demonstrate their efficiency (Garber et al., 2011).

Over the years, research has focused on different warm-up volumes, intensities, and tasks, but there are still many areas that need to be understood (Bishop, 2003; Neiva et al., 2015; Wilson et al., 2013; Zois et al., 2011). Further, there is a difference between the simulated conditions found in research and those that occur in a real context. New investigations have sought to fill this gap by trying to understand how other new procedures can be used as alternative and/or as complementary tasks to the conventional warm-up methods used by coaches and athletes (Barbosa, Barroso & Andries, 2016; Russel et al., 2015). New trends in research have therefore emerged, investigating the use of different warm-ups combined with several stretching strategies, tasks focused on post-activation potentiation (PAP), and various tools for passive warm-up that could be used to optimise the usual waiting period between warm-up and competition (Barbosa et al., 2016; Marinho, Gil, Marques, Barbosa & Neiva, 2017; McGowan, Thompson, Pyne, Raglin & Rattray, 2016; Russel et al., 2015). The present article therefore briefly reviews and highlights the newly emerging methods of active and passive warm-ups used before any competitive event to maximise performance. In brief, this review attempts to summarise and draw conclusions from the many studies that have investigated the mechanisms by which warm-up may affect performance, and changes in performance when static or active stretching, warm-up using PAP or external heating garments are used.

Stretching during warm-up

Static stretching is a common practice during physical activity and according to Knudson et al. (2001), the use of stretching as a part of a warm-up routine may improve performance and decrease the risk of muscle injury. The goal of stretching during warm-up is to reduce muscle stiffness, and increase range of motion, thus reducing the incidence of activity-related injuries (Hadala & Barrios, 2009). Several researchers have recently shown that static stretching may inhibit sports performance, especially in explosive short-term efforts (Behm & Chaouachi, 2011; Kallerud & Gleeson, 2013; Lowery et al., 2014). The decrease in muscle strength and power when using static stretching may be associated with a change in the intramuscular viscoelastic properties, resulting in a decrease in the stiffness of the muscular-tendinous junctions (Behm & Chaouachi, 2011). Even more than physiological and mechanical factors, current research has suggested that prolonged muscle stretching practices (more than 20s) could affect the efferent neural drive to the working muscles, as demonstrated by changes in electromyography signal amplitude, reducing muscle activation and resulting in the loss of force production (Trajano, Nosaka & Blazevich, 2017).

Most studies investigating the loss of strength and power performance have evaluated intermittent stretching, that is several repetitions with rest intervals, which has led to negative changes in muscle contraction by affecting the force transmission between eccentric and concentric phases of movement, and thus the stretch-shortening cycle (Marchetti et al., 2015). According to Trajano, Nosaka, Seitz and Blazevich (2014), intermittent stretching has been reported as more effective in reducing muscle stiffness compared to continuous stretching (no rest intervals), and this may therefore be associated with reduced muscle viscosity. However, Marchetti et al. (2015) found a decrease in jump height performance after either static stretching with or without rest intervals between sets, despite the increased range of motion for both stretching routines. Since both continuous and intermittent stretching were performed for the same total duration, the authors suggested that the decreased performance could be caused by a similar total load (volume x intensity) from both protocols, that affected the elastic force transference during the stretch-shortening cycle. Despite only few studies have evaluated the effects of intervals between sets of stretches on performance (Marchetti et al., 2015; Trajano et al., 2014), it seems that high-speed, explosive or reactive efforts could be reduced with different static stretching strategies.

It is well known that one of the main factors influencing performance, especially in cyclic sports such as running or cycling, is efficiency, or how effective muscles are in using the available energy (Joyner & Coyle, 2008). This could depend on factors such as morphology, elastic elements and joint mechanics (Butterfield & Herzog, 2006). Knowing that static stretching may improve the range of motion or even reduce muscle stiffness, possibly positively affecting running economy, recent studies have investigated the effects of static stretches on endurance performance. Wilson et al. (2010) investigated the effects of 16 minutes of static stretching on 30 min running at 65% of maximum oxygen uptake (VO_2max) followed by 30 min at maximal intensity on a treadmill. The authors found 3% lower performance in the last 30 min ($p<0.05$) compared to a non-stretching warm-up. Accordingly, Lowery et al. (2014) found that runners who performed six stretching exercises (3 repetitions of 30 seconds) for the lower limbs took more time to complete a 1.6 km ramp race than those who did not perform any stretches beforehand. When reducing the duration of stretching, however, the results seem to be the opposite. Takizawa, Yamaguchi and Shibata (2015) investigated the effects of short duration static stretches (20 sec without repetitions) of the lower limbs after 15 minutes of general warm-up (running at 70% VO_2max) and found no significant differences in the running time to exhaustion, at 90% of VO_2max (817.9 ± 213.7 sec), compared with general warm-up only (819.3 ± 230.6 sec). In addition, no differences in

VO_2max and blood lactate accumulation were found after the running performance test. The authors therefore suggested that endurance running performance is not affected by the inclusion of 20 sec static stretches in the warm-up exercise.

Variations in force production and performance might be due to changes in the length and stiffness of the musculotendinous unit, damage within the muscle itself that changes the contractile force capacity, reduced persistent inward current formation at the motoneurons and influencing central efferent drive, changes in electromechanical coupling and greater electromechanical delay due to the increased slack in the musculotendinous unit (for details please see studies of Behm & Chaouachi, 2011; Costa, Herda, Herda & Craemer, 2014; Ruas, McManus, Bentes & Costa, 2018). These could be considered the main mechanisms for explaining stretching induced changes on muscle force transmittal, causing impaired performances. However, by performing dynamic movements and specific activities after static stretching could reduce the possible negative effect on performance, reversing any undesirable muscular effect or associated neural effects (Behm & Chaouachi, 2011, Little & Williams, 2006; Reid et al., 2018). Marinho et al. (2017) found that a 60 m sprint after static stretching warm-up resulted in better sprint performances than after dynamic stretching or without warming-up. The authors suggested that participants benefited both from the increased range of motion effects by static stretching, that might remain elevated for 30-120 minutes (Mizuno, Matsumoto & Umemura, 2013; Power, Behm, Cahill, Carroll & Young, 2004) and from the muscle stimulation by the first 60 m sprint. Concordantly, recently Reid et al. (2018) verified that the inclusion of dynamic stretching or dynamic activity after static stretching lightened some of the stretch-induced impairments and enhanced performance compared to baseline. Thus, it should be recommended that stretching should be followed by sport specific dynamic activities that would excite neuromuscular system wherever explosive or reactive forces are necessary or any decreases in performance would be important (Behm & Chaouachi, 2011).

Evidences showed that it only 10 minutes should be needed to restore the maximal values of isometric strength after a total of 5 minutes of static stretching (Mizuno, Matsumoto & Umemura, 2014). Often, the negative effects on strength are reported to subside within 10-15 minutes (Behm, Blazevich, Kay & McHugh, 2016) but it can last up to 120 minutes following a stretch intervention (Power et al., 2004). The different results suggested that longer periods of static stretching require a longer time to recovery to baseline levels (Behm et al., 2016; Behm & Chaouachi, 2011). Others have suggested that the intensity of static stretching is a determinant of increased range of motion or even reduced performance (Freitas et al., 2014; Kataura et al., 2017). Intensities equal to or higher than 100% of maximum tolerable intensity without stretching pain increased range of motion, but decreased isometric muscle force (Kataura et al., 2017). Some studies compared different stretching intensities by using the frequency of movement and found that high frequencies of movement (100 beats/min) improved countermovement jumps, and lower frequencies (50 beats/min) improved drop jumps (Fletcher, 2010). As dynamic stretching is usually performed using a motor-pattern identical to the following physical activity, some motor-learning and adaptation could be taking place and resulting in better performances (Torres et al., 2008). The measurement of dynamic stretching intensity by the number of movements is thus still quite limited. Athletes and coaches should be careful about the duration and intensity of static stretching protocol during warm-ups, and the inclusion of 20 sec of static stretching on each target muscle group, performed at lower than the maximum tolerable intensity without pain, is recommended (Freitas et al., 2014, Kataura et al., 2017; Thompsen, Kackley, Palumbo & Faigenbaum, 2007).

Recent research suggested that dynamic stretches are safer and should be used instead of static stretching. Some studies have indicated that dynamic stretching can significantly improve power and agility (McMillian et al., 2006), sprint performance (Fletcher & Anness, 2007), vertical and horizontal jumps (Thompsen et al., 2007), when compared with static stretching only. Dynamic stretching has been reported as a facilitator of power performance (Dalrymple, Davis, Dwyer & Moir, 2010). Several reasons for this have been suggested, such as the resulting elevated muscle and body temperature, activation caused by voluntary contractions of the antagonist, stimulation of the nervous system, or a reduction in the inhibition of the antagonist muscles (Hough, Ross & Howtason, 2009). The literature tends to show that shorter durations of dynamic stretching do not affect performance (Behm & Chaouachi, 2011; Bishop et al., 2001; Hough et al., 2009). In fact, positive effects were found in vertical jump height, electromyographic signal amplitude during vertical jump (increased neuromuscular response), and isokinetic muscle isometric leg strength when dynamic stretching was performed for 30 sec repetitions for each exercise, up to a total duration of 7 minutes (Hough et al., 2009; Sekir, Arabaci, Akova & Kadagan, 2009).

The literature reports that dynamic stretching resulted in more significant improvements than static stretching, or at least, no harmful effects were found (Behm & Chaouachi, 2011). It could therefore be a safe practice to use during warm-up. Nevertheless, studies have suggested that dynamic stretching is not as effective as static stretching in increasing range of motion (Covert, Alexander, Petronis & Davis, 2010; O'Sullivan, Murray & Sainsbury, 2009). In some sports (e.g. gymnastics, some athletic disciplines) range of motion is essential to performance and therefore, coaches could choose static stretching (Wong et al., 2011). In this case, these practices should be followed by specific muscle activation activities. Behm and Chaouachi (2011) pointed out that including static stretching during the warm-up followed by dynamic activity increased range of motion and decreased injury potential without subsequent negative effect on performance. In fact, Marinho et al. (2017) recently found better performances in the second trial of 60 m sprints when including static stretches in warm-up, despite no differences were found between the static stretch or dynamic stretch warm-ups in the first 60 m of running performance. They suggested that the athletes benefitted both from the gains of a potentiation effect caused by the first sprint and from an increased muscular range of motion, whose effects might remain for 30 minutes after static stretches (Mizuno et al., 2013). This was not the only study to suggest that. Others found that static stretching had no significant effect on multiple sets of the back-squat exercise (Heisey & Kingsley, 2016). Previously to these studies, Young (2007) had already suggested that a low to moderate volume of static stretching performed between the general and specific components of the warm-up has no impact on subsequent performance.

Besides static and dynamic stretching, proprioceptive neuromuscular facilitation (PNF) is commonly used as a practice for increasing joint amplitude (Behm et al., 2016; Ruas et al., 2018). PNF incorporates static stretching and isometric contractions in a cyclical pattern no enhance joint range of motion, by contract relax technique and contract relax agonist contract technique (Sharman, Cresswell & Riek, 2006). Despite the efficacy of PNF in increasing range of motion, this technique is rarely used during warm-up routines, because the need for a partner assistance, it may be uncomfortable or painful and muscle contractions performed at highly stretched muscle lengths can result in greater cytoskeletal muscle damage (Behm et al., 2016; Butterfield & Herzog, 2006). In their review, Behm et al. (2016) estimated approximately a 4% reduction in performance after PNF stretching, with no studies presenting improved performances. Nevertheless, PNF mans an effective practice for increase range of motion and it impact on muscular performance should be further examined.

Warm-up using post-activation potentiation

PAP has been of great interest in recent years and has been demonstrated to have an ergogenic effect on performance (Borba, Ferreira-Júnior, Santos, Carmo & Coelho, 2017; Hancock, Sparks & Kullman, 2015). PAP has been defined as an increase in force production after a maximum or near maximal muscle stimulation (Kallerud & Gleeson, 2013). Specifically, PAP augments a muscle's force-generating capacity (i.e. muscle twitch and low-frequency tetanic force) as a result of the previous contractile history of the muscle cells involved in the previous contraction (Hodgson, Docherty & Robbins, 2005). The main mechanisms responsible for this aid are still not clear, but studies have tended to attribute improvements to the increased phosphorylation of the myosin regulatory light chain, especially in type II muscle fibres (MacIntosh, Robillard & Tomaras, 2012; Tillin & Bishop, 2009; Xenofondos et al., 2010). The actin-myosin interaction via calcium ions released from the sarcoplasmic reticulum and the myosin light chain kinase increase the rate of actin-myosin cross-bridging. This increased rate of cross-bridge formation allows a faster rate of force development (Tillin & Bishop, 2009; Xenofondos et al., 2010). Some research has also speculated about the elevation of excitation potentials across synaptic junctions at the spinal cord, the increase in the quantity of neurotransmitters released and their efficacy, resulting in the increased conduction of the nerve impulse to the muscle, and the quantity of recruited motor units (MacIntosh et al., 2012; Tillin & Bishop, 2009). It therefore seems that this method causes neuromuscular changes and improves type II muscle fibre activity, thus favouring performance in high-intensity and short-term activities, such as jumping, throwing and sprinting (Docherty & Hodgson, 2007).

Different PAP effects have been described by using also different kind of exercises (Hodgsonet al., 2005; Tillin & Bishop, 2009). Research has reported that including depth jumping in the warm-up protocol increased both maximal strength (Masamoto et al., 2003), sprint performance (Hilfiker, Hubner, Lorenz & Marti, 2007) and vertical jump (Hilfiker et al., 2007; Stieg et al., 2011). High external loads of strength exercise during warm-up also seemed to positively influence performance. A decrease of 3% in a 40 m sprint time was found 4 minutes after performing back squats at 85% of one-repetition maximum (1RM) (Rahimi, 2007). Moreover, 10 and 30 m sprint performance was improved by between 2 and 3% 5 minutes after performing 10 repetitions of the half back squat exercise at 90% 1RM (Chatzopoulos et al., 2007). Some controversial results have been found. For example, Kilduff et al. (2011) found that one set of 3 repetitions of a squat exercise at 87% 1RM did not improve 15 m swimming performance of swimmers, compared to a traditional in-water warm-up. This perhaps demonstrated the need for the PAP stimulus to be specific to the activity performed.

It is difficult to use external loads in a real context venue, especially when using the higher-loads. Strategies using PAP stimulation without external loads are therefore continuously studied and are important for the sport community. Jumping is beginning to be recognised as a great stimulus during traditional warm-ups for short-term competitive events. For instance, Byrne, Kenny and O'Rourke (2014) concluded that the addition of 3 depth jumps, which requires an athlete to drop from a predetermined height and perform a vertical jump immediately after ground contact, resulted in a 5% improvement of 20 m running compared to a traditional warm-up. To benefit from the effects of these kinds of practices, the ideal rest period for recovering between the jumping stimulus and main task should be between 5 and 10 minutes (Chiu et al., 2003; Kilduff et al., 2007) and should be take into account the intensity used (for instance, the jump depth and number of sets and repetitions) (Kilduff et al., 2007).

As well as the controversial results that were found (e.g. Mangus et al., 2006; Wilson et al., 2013), there was also inter-individual variability responses to PAP, and this should be of interest to coaches and athletes. The different methods used, including several types of exercises, intensities, volumes, and recoveries between stimulation and main task (Tillin & Bishop, 2009), could explain the different results found. The interaction between stimulation and fatigue has also recently been suggested as the main cause of an individual's improved or impaired performance. It seems important to determine not only the best exercise to promote physical adaptation, but also to know how much rest is needed in order to benefit from neuromuscular changes without physical impairment due to fatigue accumulation from previous stimulus. PAP should also be specific to the subsequent movement, and it depends on a subject's level and characteristics (Seitz, de Villarreal & Haff, 2014; Seitz & Haff, 2016). For instance, stronger individuals have greater type II fibre content, which has been related to a greater expression of PAP (Seitz et al., 2014; Tillin & Bishop, 2009) and possibly a more rapid recovery.

Warming-up using external heating garments

Several studies have reported significant losses in body temperature during the transition period between warm-up and main physical activity, causing a potential reduction in performance (Lovell et al., 2013; Mohr et al., 2004; Neiva et al., 2016). On the other hand, some time is required between finishing an active warm-up and the beginning of a race, to allow restoration of the acid-base balance (Bishop, 2003), restoration of phosphocreatine (Dawson et al., 1997) and to benefit from muscle potentiation (Kilduff et al., 2014). Strength and conditioning coaches should be cautious about this recovery, however, so that performance would not be compromised. In this sense, several active and passive warm-up strategies have been developed in recent years to recover from active warm-up, but at the same time to extend its main effects, such as elevated body temperature. For example, during athletics or swimming events, athletes complete their warm-up and may then have to sit in a call-room for up to 45 minutes. Active exercise is not usually possible during that period, and passive temperature maintenance could be one method used to mitigate the reduction in body temperature (Cook, Holdcroft, Drawer & Kilduff, 2013). These passive strategies could involve the use of warm clothing, survival jackets and/or heating pads. Such strategies are easily applied to the desired muscle groups to maintain Tm (Kilduff et al., 2014) and are now being investigated as a potential mechanism for optimising performance.

Tm increases rapidly in the first 3-5 minutes of active warm-up, reaches a threshold after 10-20 minutes of activity and falls exponentially within 15-30 minutes after the cessation of exercise (Faulkner et al., 2013a; Mohr et al., 2004; Neiva et al., 2016). Some years ago, Sargeant (1987) demonstrated that every 1°C reduction in Tm led to a 3% reduction in the muscle power of the lower extremities. Conversely, Racinais and Oksa (2010) showed that an increase of 1°C in Tm can result in a 2-5% improvement in the performance of the subsequent exercise. Temperature-related mechanisms were always thought to be the main focus of warm-up practices, however, the temperature attained during warm-up is reduced immediately after ending exercise. Neiva et al. (2016) found that it only took 20 minutes for the Tc to be at basal levels, which could promote a negative impact on swimming performance. Also, Mohr et al. (2004) verified 1ºC reduction in Tc during the 15 minutes time break in a soccer match that coincided with a 2ºC drop in Tm and in a 2.5% reduction in sprint performance. Concordantly, Kilduff et al. (2014) demonstrated that a decline in post-warm Tc was related to a decrease in the power of the lower body muscles (r = 0.71).

According to Russel et al. (2015) passive temperature maintenance during the interval reduces the decline in Tc, leading to an improvement in peak power as well as repeated sprint capacity. The study conducted by Cook et al. (2013) revealed a 65% increase in body temperature when active warm-up was performed with a survival jacket, and was related to a 20m sprint performance improvement. Faulkner, Ferguso, Hodder and Havenith (2013b) demonstrated that the use of athletic pants with an integrated heating element can improve peak sprint power in cycling by ~10%. The use of thermal garments during the transition phase between warm-up and subsequent exercise thus seems to be of great importance in maintaining temperature, resulting in optimised sports performance.

Warming-up using foam rolling

New warm-up practices are being developed by coaches and athletes to complement the usual warm-ups. That includes the foam rolling self-myofascial release. Foam rolling was originally thought to reduce the pain and stiffness resulting from muscular adhesions (Okamoto, Masuhara & Ikuta, 2014). The vasodilation response recorded after foam rolling, suggests that foam rolling could provide performance benefits and thus be used during a warm-up (Okamoto et al., 2014; Peacock, Krein, Silver, Sanders & VON Carlowitz, 2014). Some studies have shown that myofascial release can improve the flexibility of muscles, tendons, ligaments, and fascia by releasing tension in tight muscles or fascia (Cheatham, Kolber, Cain & Lee, 2015; Healey, Hatfield, Blanpied, Dorfman & Riebe, 2014) while increasing blood flow and circulation to the soft tissues, which in turn improves flexibility and the range of motion (MacDonald et al., 2013). This is thought to improve overall performance, however, there is little research supporting this theory. These practices have become common in the last decade as a complementary method of massage and recovery (Healey et al., 2014). In fact, the reduced feeling of fatigue could possibly extend and optimise acute and chronic performance (Healey et al., 2014).

A warm-up routine consisting of both the usual warm-up and a self-myofascial release resulted in improvements of performance between 4-7% in vertical jump, standing long jump, agility test, sprint running, and maximal strength in bench press (Peacock et al., 2014). Others found that foam rolling was effective to increase flexibility and the range of motion of the quadriceps and hamstrings without hampering muscle performance (MacDonald et al., 2013; Su, Chang, Wu, Guo & Chu, 2017). Foam rolling acutely increased range of motion immediately after implementation but did not enhance vertical jump height either alone or in combination with dynamic activities (Smith, Pridgeon & Hall, 2018). It was suggested that short bouts of foam rolling (1 session for 30-120 seconds) prior to activity does not enhance or negatively affect muscle performance but may change the perception of fatigue (Cheatham et al., 2015). Those foam rolling interventions should be preceded by a dynamic warm-up focusing on the body parts where the foam rolling technique was applied.

Nevertheless, we should acknowledge for the contradictory results that also were shown. For instance, it was found that antagonist muscle activation may be negatively affected following agonist foam rolling, and harmful for performance (Cavanaugh, Aboodarda, Hodgson & Behm, 2017). Despite the trend for increasing the short-term effects of the joint's range of motion without decreasing muscle performance, adding foam roaming techniques to other warm-up procedures seems not to result in better performances. It was therefore suggested that the use of foam rolling might be better suited for other times throughout the day rather than being part of the warm-up (Smith et al., 2018). This is a new area of research and studies are still limited by small sample sizes, and the varied methods and outcome measures used, which makes it difficult to develop a consensus on the optimal program for use (Cheatham et al., 2015; Okamoto et al., 2014; Peacock et al., 2014).

Practical aplications

After a period in which dynamic stretches were considered a viable and secure method compared to static stretches, it is now believed that implementing static stretching as an integral part of warm-up could be beneficial to specific performances. The literature demonstrates that short duration stretches do not affect long-term efforts and are recommended rather than long duration stretches. Specific exercise (i.e. short-term high-intensity stimulation of the main muscles that will be used) after stretching seems to reduce any detrimental effect and should be performed before the main task. Warm-ups that include PAP were very popular for improving performance in explosive activities. The most important thing to remember when using PAP stimulation is that different individuals reach maximum potentiation at different times. The stimulus should be specific, and the subsequent recovery may last between 5 and 10 minutes. The balance between intensity and fatigue should be considered in order to optimise performance. Another concern in recent research on warming-up is the importance of maintaining the effects of increased temperature during the transition phase between warm-up and competition. It seems evident that maintaining body temperature during the post-warm rest period is vital in order to avoid decreases in subsequent performance, and, for example, thermal clothing should be used to minimise such performance losses. Some suggestions for the warm-up procedures analysed in the current study are presented in Table 1.

Table 1 – Suggestions on stretching, post-activation potentiation and external heating procedures that could be used during warm-up

Procedures	Recommendations	Specific comments
Dynamic stretching	< 30s per repetition < 7 min total duration	Do not compromise either ballistic or long efforts performance Can be applied before, during or after the warm-up High-frequency of movements
Static stretching	< 10s per repetition < 30s per target muscle	Tolerable intensity without pain (the range of motion at pain onset) Followed by post-activation potentiation exercises Not recommended for explosive efforts (<10s duration)
Post-activation potentiation	Maximal short-term stimulus (< 30s) Performed 1 - 10 min before main exercise Examples: > 80% 1RM (< 5reps); Depth jumps (< 5reps); Short sprint (< 60m).	Main muscle groups used in the following activity Avoid fatiguing effects (individualize short-term stimulation and rest)
External heating garments	Warm clothing Survival jacket For more than 20 min of waiting: Heated garments at 40 - 43ºC	Used after warm-up (waiting period before main event) Can be combined with exercise during the waiting period

1RM: one-repetition maximum with external loads; reps: repetitions; < : less than; > : higher than.

Conclusions

Warm-up has assumed a leading role in sports-related investigations in recent years, despite some controversies. Some complementary practices have been included in warm-up by coaches and athletes and discussed by researchers regarding their effects on performance. When analysing the previous research, we found that some studies did not reveal whether the conditions assessed were randomised. Using randomized conditions can avoid learning effect of the performance variables and reduce some possible bias effect. A lack of information about whether the same warm-up procedure was used at the same time of the day could be a main limitation, since day-to-day biological variation could have an effect on other factors that could influence performance. This effect should be avoided in future research. Furthermore, several types of warm-ups, differing in volume, intensities, recoveries, tasks, have been investigated to date, but most did not use controlled conditions (for example no warm-up condition), making it difficult to compare the results and thus hindering the transfer of the findings to practice. Most studies also did not evaluate the effects of warm-up in specific environmental conditions, such as in a real competition context, with high standards of external validity. Future research should focus on the improvement of passive and active strategies after finishing warm-up so that athletes can benefit of all the positive effects of warm-up. Authors also need to provide more detailed information with practical applications for coaches and researchers. This, together with increased knowledge about the fatigue caused by warm-ups, and about recovery time may reduce the harmful effects of warm-up and maximise performance.

Collectively, the studies included in this review showed that short duration stretches can be used, followed by another specific muscle activation according to subsequent main activity (e.g. jumping exercises before sprint running). The current review showed that dynamic stretching seemed to cause more improvement than static stretching, and both depended on the duration and intensity of the exercise. External short duration maximal efforts in PAP stimulus, whether using external loads or not, and specific to the following activity, followed by few minutes of recovery, provide beneficial neuromuscular responses and improved performance in high-intensity and short-term efforts. Recent findings suggest a potential role for the inclusion of external passive heating (e.g. thermal garments) during the transition phase between warm-up and main exercise, in order to optimise subsequent performance. These recent trends could be useful tools for coaches and athletes trying to maximise performance but can also be used as training strategies to improve velocity and power sets.

Chapter 3. Experimental Studies

Study 2

The effect of ballistic exercise as pre-activation for 100m sprints

Abstract

The benefits of warm-up in sports performance has received a special interest in the current literature. However, there is a large gap of knowledge about the tasks to be performed, specifically in the real competitive environment. The purpose of the study was to verify the acute effects of a warm-up including ballistic exercises in 100m running performance. In addition, a second 100m trial was assessed to better understand the warm-up effects in training and competition. Eleven men (25.4 ± 6.2 years of age, 1.76 ± 0.08 m of height, 78.2 ± 8.6 kg of body mass) were submitted to three different protocols, in a randomized order: no-warm-up (NWU), typical warm-up (WU) and WU complemented with ballistic exercises (post-activation potentiation - PAP). Biomechanical, physiological and psychophysiological variables were assessed. Differences were found between the three conditions assessed in the first 100m sprint with 7.4% and 7.6% faster performances after the WU and PAP, compared to NWU. Stride length was higher in the second part of the 100m after PAP compared with WU. These results highlight the positive effects of warm-up for sprinting performance. The inclusion of ballistic exercises, besides being used to improve sprint performance, can increase stride length in the final of the 100m race.

Key-Words: Warm-up; Performance; Repeated-sprint; Physiology; Biomechanics

Introduction

Warm-up practices have been used to prepare the athlete for training and/or competition (Silva, Neiva, Marques, Izquierdo & Marinho, 2018). It is believed that a well-designed warm-up causes physiological changes and helps the athlete to increase the mental focus for the next task, allowing them to optimize the performance (Neiva et al., 2015). The main effects of warming up derived from increased body temperature and from the muscle movement, both contributing to decreased joint and muscle stiffness, improved nerve conduction rate, efficient metabolic reactions, increased blood flow to the active muscles, increased oxygen uptake, and to post-activation potentiation (PAP) mechanisms (Kilduff, West, Williams & Cook, 2013; Swanson, 2006).

There has been an increase in interest in the warm-up issue, evidenced by the number of recent studies and most reporting high benefits for performance in different sports and activities (Marinho, Gil, Marques, Barbosa & Neiva, 2017; Neiva et al., 2014; Neiva, Marques, Barbosa, Izquierdo & Marinho, 2014). Specifically, in running, it is now well stablished that warm-up improve sprint performance (Marinho et al., 2017; Silva et al., 2018; Zois, Bishop, Ball & Aughey, 2011). Usually, warm-up included a brief period of low intensity aerobic (eg, light to submaximal running) and stretching exercises, followed by specific exercises related with the following activity and/or sport (Andrade et al., 2015; Silva et al., 2018). During this specific phase of warm-up, the coaches and the athletes have been experiencing several exercises for the same purpose, such as dynamic and static stretching (Kallerud & Gleeson, 2013), agility exercises and ballistics (Perrier, Pavol & Hoffman, 2011). These last, the ballistic exercises, are a recent trend of specific warm-up and are believed to cause a PAP phenomenon, thus enhancing the performance (Blagrove, Holding, Patterson, Howatson & Hayes, 2019; Gil, Neiva, Sousa, Marques & Marinho, 2019).

Researchers have looked at the PAP phenomenon, suggesting that it might improve muscle power manifestations (Hodgson, Docherty & Robbins, 2005; Seitz, de Villarreal & Haff, 2014). This increase in force production usually happens after a maximum or near maximal muscle stimulation (Kallerud & Gleeson, 2013). PAP seems to augment muscle force generating capacity as a result of the previous contractile history of the muscle cells involved in the previous contraction (Hodgson et al., 2005). There is an acute effect that increases the speed of conduction of the nerve impulse to the muscle, increases the number of recruited motor units and improves the interaction mechanism of contractile filaments (Saez Saez de Villarreal, González-Badillo & Izquierdo, 2007). The main mechanisms responsible for this are not totally clear, but studies attributed improvements to the increased phosphorylation of the myosin regulatory light chain (MacIntosh, Robillard & Tomaras, 2012; Tillin & Bishop, 2009; Xenofondos et al., 2010). PAP seems to cause neuromuscular changes and improves type II muscle fibre activity, thus favouring performance in short-term maximal efforts (Gil et al., 2019).

An improvement of 3% was found in 40m sprints after performing back squats at 85% of one-repetition maximum (1RM) (Rahimi, 2007). Improvements of 2 and 3% were also found in 10 and 30m sprints after 10repetitions of half back squat exercise at 90% 1RM (Chatzopoulos et al., 2007). Nevertheless, Kilduff et al. (2011) found that one set of 3 repetitions of a squat exercise at 87% 1RM did not improve 15m swimming performance, compared to a traditional in-water warm-up. Previous research mainly focused on high external loads of strength exercise during warm-up and it is known that it cannot be applied in a real competition context (Gil et al., 2019; Kilduff, Owen, Bevan, Bennett & Kingsley, 2008; Rahimi, 2007). There is a real need for understanding the effects of the PAP using some usual tasks that can be reproduced in real competition-venue. The first studies on this revealed that including depth jumping in the warm-up protocol increased both maximal strength (Masamoto, Larsen, Gates & Faigenbaum, 2003) and vertical jump (Hilfiker, Hubner, Lorenz & Marti, 2007; Stieg et al., 2011). Byrne, Kenny and O'Rourke (2014) concluded that the addition of 3 depth jumps resulted in a 5% improvement of 20 m running compared to a traditional warm-up. However, few is known when these ballistic exercises are used before Olympic racing distances, such as the 100 m. Moreover, little is known about the effects of using PAP strategies on the biomechanical variables during running. Running performance depends on the stride parameters and, for instance, the optimal ratio between stride length (SL) and stride frequency (SF) enable maximal sprinting velocity and efficiency (Krzysztof & Mero, 2013). This relationship is conditioned by the neuromuscular regulation of movement, morphological characteristics, motor abilities and energy substrates (Coh, Milanovic & Kampmiller, 2001; Prampero et al., 2005), all that can be influenced by warm-up tasks (Gil et al., 2019; Neiva et al., 2014; Silva et al., 2018).

Therefore, it was hypothesized that a warm-up that included ballistic exercises would improve 100m running performance, by changing the stride parameters (SL and SF) and physiological response. So, the primary aim of the current study was to verify the acute effects of a warm-up including ballistic exercises inducing a PAP, easy to apply on a real competition context, in 100m running performance. In addition, a second 100m trial was assessed to better understand the warm-up effects during competition and training. To the best of our knowledge, no previous investigation used a second repetition, and this is important to understand the neuromuscular and metabolic responses, helping to develop optimized training strategies. Repeated efforts have been used as determinants for success in a wide range of sports and may be associated with neuromuscular and metabolic factors that influence performance (Spencer, Bishop, Dawson & Goodman, 2005; Taylor, Weston & Portas, 2013). The primary outcomes for our study are the 100m running performance (time) and biomechanical variables (SL and SF). Secondary outcomes included physiological (lactate concentration ([La-]) and heart rate (HR)) and psicoshpyiological (ratings of perceived exertion (RPE)) variables.

Materials and methods

Participants

Eleven men aged 20-36 years (mean ± SD: 25.4 ± 6.2 years of age, 1.76 ± 0.08 m of height, 78.21 ± 8.59 kg of body mass) volunteered to participate in this study. Participants were physically active sport science students. Each individual was asked to report any previous illness, injury or other physical issue that would hinder their performance. Participants were included on the basis that they were healthy, injury free, and engaged in physical activity regularly with an experience of running and testing for the last 2 years, although they were not competitive sprinters. Criteria of exclusion from the study was the evidence of any medical or orthopedic problem, a self-reported fitness classification below moderately active, or any other self-reported issue that would endanger their own health (assessed via questionnaire). After local ethics board approval, ensuring compliance with the Declaration of Helsinki, the subjects were informed about the study procedures, and a written informed consent was signed.

Design

The purpose of the present study was to evaluate the effects of typical warm-up procedures (WU), the inclusion of PAP and no warm-up (NWU) on 100m running performance, analyzing biomechanical, physiological and psychophysiological variables.

Each participant completed two 100m time-trials after each warm-up condition, in a randomized order, separated by 48h. The WU design was based on literature recommendations (Taylor et al., 2013; Zois et al., 2011) and included a low intensity aerobic component followed by specific running tasks. The PAP protocol included lower body ballistic exercises according to previous suggestions (Maloney, Turner & Fletcher, 2014) after completing WU. During the NWU condition, the subjects were asked not to perform any type of action or movement prior to the 100m sprint, remaining seated for 5min. This design was able to test whether the inclusion of PAP strategies during warm-ups affected running performance.

Experimental Procedures

All the procedures took place at the same time of the day (8:00 – 12:00 AM) for each participant under the same environmental conditions (~22°C air temperature and ~60% of humidity) in an athletics track facility. The participants were familiarized with the warm-up procedures 72 hours before the experiments, and they were reminded to maintain the same routines during the assessment days, avoiding strenuous exercise, and abstaining from consuming caffeine 48 hours before testing.

After arriving, each participant remained seated for 5min and baseline measurements of heart rate (HR; Vantage NV; Polar, Kempele, Finland) and blood lactate concentration ([La-]; Lactate Pro LT 1710; Arkray Inc., Kyoto, Japan) were then assessed. Each volunteer was then randomly assigned to a warm-up protocol (Figure 1).

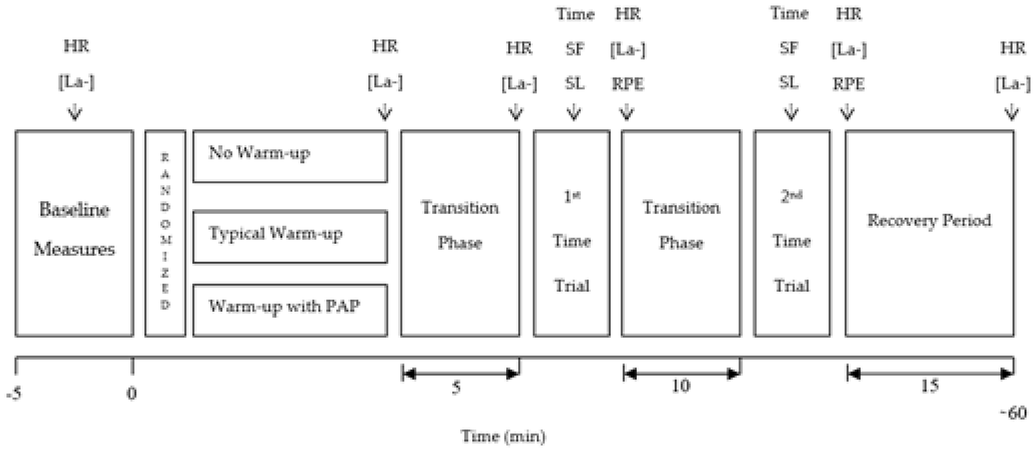

Figure 1. Schematic representation of the study design and testing procedures used. HR = heart rate; [La-] = blood lactate concentration; SF = stride frequency; SL = stride length; RPE = ratings of perceived exertion.

Warm-up Protocols

The warm-ups were designed based on research (Silva et al., 2018; Zois et al., 2011; Taylor et al., 2013) and with the help of an experienced coach. The main difference between the warm-ups were the inclusion of lower-body ballistic exercises to stimulate PAP. WU comprised 5min of easy run (lower than 65% of estimated maximal HR), eight exercise drills (20m repetitions with 10s of recovery between them), such as rhythmic jumps from foot to foot, ankle drills, skippings drills, high-knee running. Then, these technical exercises were followed by 2x40m running at gradually increasing intensity. In the PAP condition, the participants performed the WU followed by 2 sets of 5 depth jumps from a box of 70cm height (3min recovery) as suggested by Maloney et al. (2014). Each jump was performed by stepping off a box with one foot, landing with bent knees, then immediately jumping with maximal effort. The subjects were instructed to jump as quick and high as possible and to keep their hands on their hips to eliminate any contribution of arm swing (Andrade et al., 2015; Byrne et al., 2014).

Time-trial performance

Once the participants finished warming-up, they remained seated for 5min before performing the 100m time-trials. The subjects started from a standing position with the trunk bent forward and the lower limbs apart and slightly bent, positioned behind the starting line. After official commands, each participant started maximal running using a standing start with the lead-off foot placed 1m behind the first timing gate. Times were measured by Photocell timing gates (Brower photocells, Wireless Sprint System, USA) placed at 0, 50, and 100m so that the times needed to cover 0–50m (T0-50), 50–100m (T50-100) and 0–100m (T100) could be determined. After 10min rest, the subjects performed a second 100m sprint.

Kinematics

All the procedures were recorded by two video cameras (Casio Exilim Ex-F1, f=30Hz) placed perpendicular to the running track. This enabled the acquisition of basic kinematic data such as the number of strides performed by each subject, the average SL and average stride SF calculations, between 0 and 50m and between 50 and 100m, using an open-source software (Kinovea, version 0.8.15). In running, a stride is defined as the time between two consecutive specific discrete events, normally defined as two consecutive foot strikes on the same foot. SL is defined as the distance traveled during a stride and SF is defined as the rate of strides per min. SF was converted to International System Units (Hz) for further analysis. Knowing the time performed and thus the running velocity, SL was determined from the division of running velocity by SF (Hamill &Knutzen, 2009; Hunter, Marshall & McNair, 2004).

Physiological and Psychophysiological Variables

Capillary blood samples for [La-] assessment were collected from the fingertips before and 5min after warm-ups, 5min after each 100m sprint to obtain the highest value ([La-]peak) (Goodwin, Harris, Hernández & Gladden, 2007), and after 15min of recovery. HR was assessed before and after each warm-up (5min), immediately after each time-trial (1min) and after 15min of recovery. Additionally, the rating of perceived exertion (RPE) were recorded using a 10-points Borg scale modified (Borg, 1998), modified by Foster et al. (2001) after warm-ups and after the time-trials.

Statistical Analysis

Standard statistical methods were used for the calculation of mean and standard desviations (SD), and 95% confidence intervals for all variables. The normality of all distributions was verified using Shapiro-Wilk tests. Data for all variables analysed were homogeneous and normally distributed. The effect of the warm-up procedures was analyzed by an ANOVA for repeated measures, with sphericity checked using Mauchly's test. When the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse-Geisser procedure. Bonferroni post-hoc analysis were performed to further investigate the effect of each condition. All these statistical procedures were performed using IBM SPSS Statistics for Windows®, version 22.0. (Armonk, NY, USA: IBM Corp.) and the level of statistical significance was set at $p \leq 0.05$. In addition, the effect size was calculated to estimate variance between conditions (partial eta squared: η_p^2) and Hedges'g (effect size - ES) for within-subjects' comparisons using the Excel spreadsheet by Lakens (2013). ES values of 0.20, 0.60, 1.20 and 2.00 were considered small, moderate, large and very large magnitudes, respectively (Hopkins, Marshall, Batterham & Hanin, 2009). For η_p^2, cut-off values were interpreted as 0.01 for small, 0.09 for moderate and 0.25 for large.

Results

Before warm-up, the physiological variables were not different between conditions. Baseline measurements of HR (70 ± 7 bpm vs. 69 ± 7 bpm vs. 70 ± 7 bpm; $F = 0.35$, $p = 0.71$, $\eta_p^2 = 0.04$) and [La-] (2.5 ± 0.6 mmol·L-1 vs. 2.5 ± 0.6 mmol·L-1 vs. 2.5 ± 0.6 mmol·L-1; $F = 0.41$, $p = 0.67$, $\eta_p^2 = 0.04$) were similar between the three conditions.

Table 1 presents a comparison between the HR, the [La-] immediately after the warm-ups. It is possible to verify significant differences in HR ($F = 19.80$, $p < 0.001$, $\eta_p^2 = 0.69$) and [La-] ($F = 35.29$, $p < 0.00$, $\eta_p^2 = 0.80$), with higher values for either warm-ups compared with no warm-up condition. No differences were found in perceived exertion between warm-ups performed (WU: 4.27 ± 1.27 vs. PAP: 3.80 ± 1.40; $p = 0.34$, ES = 0.32).

Table 1. Mean ± SD values (95% confidence interval) of physiological responses to no-warm-up (NWU), typical warm-up (WU) and post-activation potentiation warm-up (PAP) (n=11). P-values and effect sizes (ES) are also presented.

				NWU vs WU		NWU vs PAP		WU vs PAP	
	NWU	**WU**	**PAP**	**p-value**	**ES**	**p-value**	**ES**	**p-value**	**ES**
HR [bpm]	72 ± 6 (68, 76)	99 ± 13 (89, 108)	91 ± 9 (86, 97)	**<0.01****	2.72	**<0.01****	2.43	0.42	0.70
$[La^-]$ $[mmol \cdot L^{-1}]$	2.5 ± 0.6 (2.0, 2.9)	4.7 ± 1.1 (3.9, 5.5)	4.4 ± 1.0 (3.7, 5.1)	**<0.01****	2.48	**<0.01****	2.27	0.63	0.27

Mean ± SDvalues (95% confidence limits). $[La^-]$ = blood lactate concentration. HR = heart rate. ** $p \leq 0.01$.

Table 2 presents the results recorded in the first 100m sprint after NWU, WU and PAP. Large differences were found between the three conditions assessed (F = 12.52, p = 0.005, η_p^2= 0.58) in the 100m sprint. The participants were 7.44% and 7.57% faster after the WU and PAP, compared to NWU, respectively. Moreover, four of them were faster after WU and seven were faster after PAP.

Warm-ups assessed resulted also in large effects in the SF during the first 50m (F = 3.81, p = 0.07, η_p^2= 0.30) and the second 50m (F = 9.29, p = 0.01, η_p^2= 0.51) of the time-trial. The SL showed to be clearly different only in the second 50m of the time-trial (F = 4.14, p = 0.03, η_p^2= 0.32). After trial, no significant differences were found in [La-] values (F = 2.16, p = 0.14, η_p^2= 0.19), HR (F = 1.20, p = 0.32, η_p^2= 0.12) and RPE values (F = 0.18, p = 0.73, η_p^2 = 0.02).

Table 2. Mean ± SD values of the first 100-m time trial, biomechanical and psychophysiological variables assessed during experimental protocols: no-warm-up (NWU), typical warm-up (WU) and with post-activation potentiation (PAP) (n=11).

				NWU vs WU		**NWU vs PAP**		**WU vs PAP**	
	NWU	**WU**	**PAP**	**p-value**	**ES**	**p-value**	**ES**	**p-value**	**ES**
T0-50 [s]	7.30 ± 0.68 (6.85, 7.64)	7.01 ± 0.58 (6.68, 7.34)	7.00 ± 0.62 (6.61, 7.39)	0.34	0.44	0.39	0.44	1.00	0.02
T50-100 [s]	8.69 ± 0.69 (8.20, 9.18)	7.66 ± 0.73 (7.13, 8.18)	7.66 ± 0.91 (7.01, 8.31)	**0.03***	1.39	**0.04***	1.23	1.00	0.00
T100 [s]	15.99 ± 0.96 (15.30, 16.68)	14.67 ± 1.29 (13.75, 15.60)	14.66 ± 1.52 (13.58, 15.74)	**0.01*****	1.12	**0.02***	1.03	1.00	0.01
T0-50 SF [Hz]	1.97 ± 0.19 (1.84, 2.11)	2.08 ± 0.14 (1.97, 2.18)	2.04 ± 0.13 (1.95, 2.13)	0.12	0.64	0.55	0.42	0.15	0.28
T50-100 SF [Hz]	1.72 ± 0.21 (1.57, 1.87)	1.89 ± 0.11 (1.81, 1.96)	1.91 ± 0.10 (1.84, 1.98)	**0.05***	1.02	**0.03****	1.17	0.77	0.18
T0-50 SL [m]	3.51 ± 0.32 (3.28, 3.75)	3.47 ± 0.34 (3.23, 3.71)	3.54 ± 0.36 (3.3, 3.86)	0.74	0.12	1.00	0.08	**0.01****	0.19
T50-100 SL [m]	3.40 ± 0.33 (3.16, 3.63)	3.51 ± 0.42 (3.21, 3.81)	3.47 ± 0.42 (3.17, 3.77)	0.10	0.28	0.42	0.18	0.48	0.09
HR [bpm]	148 ± 24 (131, 165)	156 ± 22 (140, 172)	162 ± 18 (149, 175)	1.00	0.33	0.43	0.64	0.84	0.29
$[La^-]_{peak}$ $[mmol \cdot L^{-1}]$	7.6 ± 1.8 (6.3, 8.8)	8.5 ± 1.3 (7.5, 9.4)	8.9 ± 1.5 (7.8, 10.1)	0.38	0.56	0.32	0.75	1.00	0.27
RPE	6.00 ± 1.83 (4.69, 7.31)	6.60 ± 1.43 (5.58, 7.62)	6.49 ± 1.27 (5.58, 7.39)	1.00	0.35	0.76	0.30	1.00	0.08

Mean ± SDvalues (95% confidence limits). HR = heart rate. $[La^-]$ = blood lactate concentration. RPE = ratings of perceived exertion. ** p ≤ 0.01 and * ** p ≤ 0.05.

In the second 100m sprint (Table 3), no differences were found between warm-ups condition (F = 0.58, p = 0.50, η_p^2= 0.06). Nevertheless, we verified that there was a 6.12% improvement from the first to the second sprint of 100 m in the NWU condition, while the same did not occur in the other conditions. The different responses to each warm-up condition in the 100m time trials can be easily confirmed in Figure 2.

Table 3. Mean ± SD values of the second 100-m time-trial, biomechanical and psychophysiological variables assessed during experimental protocols: no-warm-up (NWU), typical warm-up (WU) and with post-activation potentiation (PAP) (n=11).

				NWU vs WU		**NWU vs PAP**		**WU vs PAP**	
	NWU	**WU**	**PAP**	**p-value**	**ES**	**p-value**	**ES**	**p-value**	**ES**
T0-50 [s]	7.16 ± 0.59 (6.73, 7.58)	7.03 ± 0.56 (6.63, 7.43)	6.97 ± 0.59 (6.55, 7.39)	0.80	0.22	0.32	0.31	1.00	0.10
T50-100 [s]	7.76 ± 0.61 (7.33, 8.20)	7.70 ± 0.82 (7.11, 8.29)	7.78 ± 0.98 (7.08, 8.48)	1.00	0.08	1.00	0.02	1.00	0.09
T100 [s]	14.92 ± 1.16 (14.09, 15.75)	14.73 ± 1.36 (13.76, 15.70)	14.75 ± 1.52 (13.67, 15.84)	1.00	0.14	1.00	0.12	1.00	0.01
T0-50 SF [Hz]	1.98 ± 0.16 (1.87, 2.10)	2.04 ± 0.09 (1.97, 2.11)	2.02 ± 0.12 (1.94, 2.10)	0.42	0.46	0.82	0.27	1.00	0.18
T50-100 SF [Hz]	1.88 ± 0.14 (1.77, 1.98)	1.89 ± 0.12 (1.80, 1.97)	1.86 ± 0.13 (1.77, 1.95)	1.00	0.07	1.00	0.14	1.00	0.23
T0-50 SL [m]	3.56 ± 0.32 (3.33, 3.79)	3.51 ± 0.32 (3.28, 3.74)	3.59 ± 0.38 (3.32, 3.86)	0.74	0.15	1.00	0.08	0.18	0.22
T50-100 SL [m]	3.47 ± 0.39 (3.19, 3.75)	3.49 ± 0.38 (3.22, 3.75)	3.52 ± 0.47 (3.18, 3.85)	1.00	0.05	1.00	0.11	1.00	0.07
HR [bpm]	164 ± 10 (157, 171)	161 ± 29 (140, 182)	172 ± 20 (158, 186)	1.00	0.15	0.25	0.51	0.63	0.43
$[La^-]_{peak}$ $[mmol{\cdot}L^{-1}]$	10.6 ± 1.6 (9.5, 11.7)	11.7 ± 1.6 (10.6, 12.8)	11.7 ± 1.9 (10.4, 13.0)	0.16	0.66	0.43	0.60	1.00	0.00
RPE	7.10 ± 1.66 (5.91, 8.29)	7.00 ± 1.41 (5.99, 8.01)	7.30 ± 1.06 (6.65, 8.06)	1.00	0.06	1.00	0.14	0.84	0.23

Mean ± SDvalues (95% confidence limits). HR = heart rate. $[La^-]$ = blood lactate concentration. RPE = ratings of perceived exertion. ** p ≤ 0.01 and * ** p ≤ 0.05.

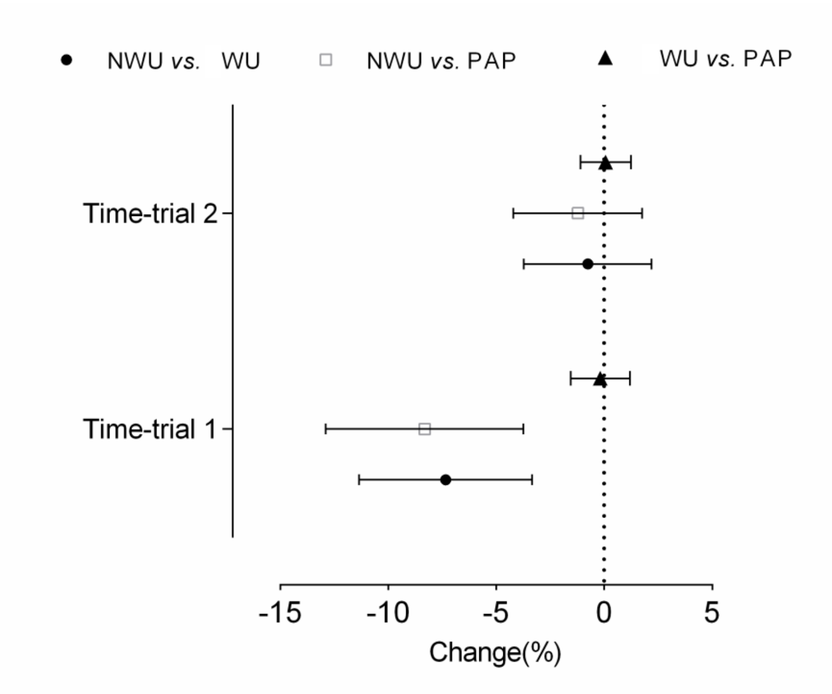

Figure 2. Mean changes (± 90% CI) verified between conditions, specifically no warm-up (NWU), after typical warm-up (WU) and after WU complemented with ballistic exercises (PAP) in each 100m time-trial.

No significant differences were found in running kinematics during the second sprint, specifically regarding the SF in the first ($F = 1.89$, $p = 0.18$, $\eta_p^2 = 0.17$) and second 50m ($F = 0.33$, $p = 0.72$, $\eta_p^2 = 0.04$), and regarding the SL in the first ($F = 2.19$, $p = 0.14$, $\eta_p^2 = 0.19$) and second 50m ($F = 0.68$, $p = 0.52$, $\eta_p^2 = 0.07$). No significant differences were found in [La-] values ($F = 2.83$, $p = 0.09$, $\eta_p^2 = 0.24$) HR ($F = 1.21$, $p = 0.32$, $\eta_p^2 = 0.12$), and RPE values ($F = 0.18$, $p = 0.73$, $\eta_p^2 = 0.02$) after the second time trial.

No differences were found after 15min of recovery in the HR (NWU: 94 ± 8bpm vs. WU: 97 ± 18bpm vs. PAP: 96 ± 6bpm; $F = 0.17$, $p = 0.84$, $\eta_p^2 = 0.02$), and in the [La-] values (7.8 ± 1.3 mmol·L-1 vs. 7.9 ± 1.3 mmol·L-1 vs. 7.7 ± 1.0 mmol·L-1; $F = 0.37$, $p = 0.70$, $\eta_p^2 = 0.04$).

Discussion

The main purpose of the current study was to verify the acute effects of a warm-up including ballistic exercises, easy to apply on a real competition context, in 100m running performance. It was intended to benefit from some PAP, and thus optimizing sprint running performance. This hypothesis was partial confirmed by the increased performance verified in the first sprint compared with the non-existence of warm-up. Nevertheless, by including some post-activation potentiation strategies such as the ballistic exercises, there were no additional effects in performance compared to the typical warm-up procedures. These results are in accordance with previous scientific evidences that reported optimized sprint performances after a typical warm-up or a PAP warm-up (e.g. Kilduff et al., 2008; West et al., 2013) but failed to evidence additional improvement in performances after the use of ballistic exercises, as expected (e.g. Johnson, Baudin, Ley & Collins, 2019; Till & Cooke, 2009). Both warm-ups resulted in higher SF in the second part of the first time-trial compared with no warm-up. Interestingly, SL was higher in the second part of the 100m after PAP compared with WU. This suggest that there are some specific technical adaptations that occur as response to different warm-up stimulations.

The warm-up is intended to optimize the athletes' preparedness, by increasing temperature, blood flow and muscle and metabolic efficiency to produce faster responses which are determinant to performance (Neiva et al., 2014; Silva et al., 2018). The ability of the muscle to produce force can be acutely modified by warm-up by including some conditioning muscle contractions (Kilduff et al., 2011). The PAP elicits transient improvements in performance and has been investigated as a strategy to include during warm-up for increasing performance (Kilduff et al., 2008; West et al., 2013). The common exercises related to potentiation post activation phenomenon have used heavy-load (75 – 95% 1RM) resistance exercise (Kilduff et al., 2008). However, ballistic exercises can be used as alternative since these are usually related with type II motor units' recruitment (Turner, Bellhouse, Kilduff & Russell, 2015). In fact, ballistic activities are more practical and feasible before competition compared to exercises requiring high-intensity external loads. That was the main reason for the assessment of ballistic exercises during warm-up in the current studies. Recent studies found some benefits by using depth jumping during the warm-up protocol to both maximal strength (Masamoto et al., 2003), sprint performance (Till & Cooke, 2009) and vertical jump (Stieg et al., 2011; Till & Cooke, 2009). However, to the best of our knowledge, no studies evaluated this warm-up strategy when applied to official running distances such as the 100m race and tried to understand the biomechanical responses during the race.

The results showed that the 100m running performance was positively influenced by the warm-up. All the participants performed better after either warm-ups and, despite no statistically significant differences were found between WU and PAP ($p = 1.00$, $ES = 0.01$), seven athletes recorded their best times after PAP. This could mean that there might be an individual response to PAP stimulation, as already highlighted by Till and Cook (2009). These authors found no differences in 20m running performance by adding different post-activation potentiation strategies to usual warm-up, such as deadlift (5 repetitions at 5 repetitions maximum), or tuck jump (5 repetitions), or isometric maximum voluntary knee extensions (3 repetitions for 3s) (Till & Cook, 2009). Nevertheless, others found positive effects on the use of ballistic exercises in running performance. Byrne et al. (2014) verified that a brief warm-up of 5 min of running, dynamic stretches and three vertical jumps resulted in 5% better performance in 20m sprint compared to the warm-up without the jumps. Accordingly, Lima et al. (2011) found that 2x5 jumps from a height of 0.75m caused 2% faster 50m sprint performance. More recently, Turner et al. (2015) found that the utilization of alternate-leg plyometric bounding provides an effective strategy for acutely improving sprint acceleration performance (10 and 20m). Thus, it would be expected that there will be greater differences between the warm-ups performed, since the use of ballistic exercises during warm-up have been suggested as potentiating performance in explosive and short-term efforts (Hodgson et al., 2005; Seitz et al., 2014). In fact, most studies looked at race distances markedly lower than that used in the current study. This longer distance might have caused the potentiation effects to disappear among other determinants of performance (Gastin, 2001).

Maximal running performance results from an optimal ratio between SF and SL (Krzysztof & Mero, 2013). Some studies claimed SL to be the most influencing variable for maximal running velocity (Mackala, 2007) while others suggested the SF (Krzysztof & Mero, 2013). Nevertheless, it is a fact that the runners adjust the SL and the SF to get the most efficient running, optimizing velocity according to their own characteristics (Salo, Bezodis, Batterham & Kerwin, 2011). In the current study, better sprint times after warm-up could be caused by the ability to maintain a higher SF on final 50m of the 100m sprint without compromising the SL values. This situation did not occur in the NWU condition. Our results corroborated with previous research that suggested that there is a biomechanical adaptation in response to different warm-ups procedures (Neiva et al., 2015; Neiva et al., 2017).

Interestingly, the running kinematics showed to be different in response to WU or PAP. In the PAP condition, the participants showed greater SL in the beginning of the race, contrarily to the SF that showed to be lower, compared with the WU condition. The PAP seemed to acutely stimulate the force required for an increased SL and perhaps improving the efficiency of the movement, that remains higher in the beginning of the second sprint. The effects of warm-up on acute motor learning and on sensorimotor responses could lead to different biomechanical movement patterns after different warm-ups (Neiva et al., 2017). Our WU ended with some specific running exercises and the PAP ended with jumps. It is a fact that the running exercises and running acceleration exercises could have prepared the participants to perform higher SF, while the jumps generated a greater capacity to exert muscular power, hence more effective force in less time and thereupon greater SL. So, this different biomechanical running adaptation might be partially explained by the specificity of the preload stimulus, since the vertical jump is biomechanically different from horizontal running.

The physiological variables showed an increased response to warm-up, with higher HR and [La-] values after warm-up, and within the range of values that some authors suggested to be adequate for a proper warm-up (Neiva et al., 2017; Raccuglia et al., 2016). This perhaps explain the better response in the first sprint after either warm-up procedures. Nevertheless, those differences disappeared after the first time-trial, which may be seen as a specific warm-up stimulus that in some way places the participant at a similar preparation level. The first sprint enhanced the neuromotor excitability that resulted in performance optimization in a second 100m sprint (Marinho et al., 2017; Spencer et al., 2005). The non-existence of differences between in HR and [La-] values might suggest that PAP stimulation by the ballistic exercises used were not enough to induce physiological stress. Once again, this could be caused by the lack of specificity of the jumps and/or an insufficient load to stimulate some higher responses in PAP. We should be aware of a possible individualized effect of PAP stimulation, that was already documented before (Seitz et al., 2014; Wilson et al., 2013). Moreover, we could speculate that the interval after PAP was not adequate for each runner (Baudry & Duchateau, 2007; Sue, Adams & DeBeliso, 2016). It is known that the PAP effect may last for 5 to 10 min (Sue et al., 2016) and within this period, there are different moments of maximal potentiation for each individual (Kilduff et al., 2008). However, our results were reliable and enlightening about the use of both warm-up procedures and that PAP could be used as an alternative to traditional warm-up.

Some limitations, however, should be addressed. In fact, our results could not entirely be extrapolated to performance of higher skilled sprints during official events since the participants were not sprint specialists/athletes and it is known that post-activation potentiation could be influenced by training levels (Xenofondos et al., 2010). Also, further studies should include a larger number of participants and include females to clarify some of the analyzed findings. However, we took several steps to strengthen our statistical analysis as described in the statistical section. Future research should investigate different PAP strategies (e.g. combining different jumps or short-term sprints) and different recovery times between the warm-up and the race. Moreover, other evaluation methods could be used to complement our measures and to deepen our findings, such as body temperature and other biomechanical variables (e.g. contact time and horizonal forces production). Considering our limitations, readers should interpret our results with discernment. Even so, the current findings still relevant for coaches and researchers for increased knowledge on warm-up and the effects on performance.

Conclusion

The results suggested that 100 m running performance is positively influenced by warm-up procedures, evidenced by the best results after the WU and the PAP compared to NWU condition. Moreover, our results suggested that 100 m is equally optimized after WU or PAP, but with different running kinematics. Thus, in support of our original hypotheses, we have demonstrated that warming up benefits the 100 m running performance and that ballistic exercises, easy to perform by using body mass, can be used as an alternative to typical warm-up procedures.

Some practical applications can be drawn. It seems clear that 100m sprinters should warm-up for better competitive and training performances. When no warm-up is possible, a single

100m trial can be enough to stimulate and prepare the athlete for that unusual situation. Yet, it is usually possible to warm-up before the race or training session and in this case, the PAP could be included in the warm-up to potentiate some individual benefits. The incorporation of ballistic exercises (e.g. vertical jumps) into the warm-up protocol is a far more practical approach than using external heavy loads to cause PAP and has demonstrated to be equally effective in 100 m running. Moreover, if the individual 100m race strategy depends on having a higher SF, a typical warm-up should be used, whereas if higher SL is needed, the warm-up including ballistic exercises should be used.

Our data highlight the need for tailored and customized warm-up designs and specifically PAP strategies during warm-up, because participants had different individual responses. Coaches usually have several athletes training or competing and individualization is difficult. However, the current results alerts coaches and researchers that ballistic exercises can be used to potentiate sprint running performance for some sprinters. The current study took a novel approach to warm-up research by examining the effects of including PAP exercises (i.e. ballistic exercises) in running performance and in running stride kinematics.

Study 3

Does the inclusion of ballistic exercises during warm-up enhance short distance running performance?

Abstract

The warm-up is considered essential to optimize running performance, but little is known about the effect of specific warm-up tasks, specifically in the real competitive context. The current study aimed to verify the acute effects of a warm-up including ballistic exercises in 30m running performance. In addition, a second 30m trial was assessed to better understand the warm-up effects in training/competition. Twenty-two men (19.32±1.43 years-old) randomly completed the time-trials on separate days and after a typical warm-up (WU), a WU complemented with ballistic exercises (post-activation potetiation - PAP) or no warm-up (NWU). Biomechanical, physiological and psychophysiological variables were assessed. The participants were 1.9% faster in the first 30m sprint after WU compared with NWU, mainly increased performance in the first 15m (p=0.03, ES=0.48). WU resulted in greater stride length in the last 15m of the first sprint. PAP did not differ from NWU and WU, despite eight participants performed better after this warm-up. These results highlight the positive effects of warm-up for sprinting, despite failed to evidence positive effects when ballistic exercises are included. In addition, the influence of warm-up in the running technique was highlighted by the changes in the running kinematics and a need for individualization of warm-up procedures.

Key-Words: Warm-up; Post-activation potentiation; Performance; Time-trial; Physiology; Biomechanics

Introduction

The benefits of warm-up for sport performance and/or even for injury prevention are widely accepted (McGowan, Pyne, Thompson & Rattray, 2015; Neiva et al., 2014; Silva, Neiva, Marques, Izquierdo & Marinho, 2018, Hammami, Zois, Slimani, Russel & Bouhlel, 2018). Although most of the published research has shown the positive effects of warm-up on physical performance (Fradkin, Zazryn & Smoliga, 2010; Hammami et al., 2018), the impact of those effects depends on the warm-up structure (Frikha, Chaâri, Mezghanni & Souissi, 2016; Neiva et al., 2017a; Zochowski, Johnson & Sleivert, 2007). Innovative methods have been purposed to be included in warm-up procedures by recent studies (Gil, Neiva, Sousa, Marques & Marinho, 2019). Specifically, the post-activation potentiation (PAP) by using some specific exercises such as squat repetitions with external loads or jumping, has been of a great interest in recent years (Barbosa, Barroso & Andries, 2016; Duncan, Thurgood & Oxford, 2014; Gil et al., 2019; Marinho, Gil, Marques, Barbosa & Neiva, 2017).

PAP phenomenon has been briefly described as an acute increase in force production after a maximum or near maximal muscle stimulation (Kallerud & Gleeson, 2013). The benefits of warm-up using PAP have been reported, showing enhanced maximal force production (Mettler & Griffin, 2012; Smith et al., 2014), and improved sprint and vertical jumping performances (Hilfiker, Hubner, Lorenz, & Marti, 2007; Stieg et al., 2011). For example, Bevan et al. (2010) verified a significant improvement in 5 and 10m sprint performance after performing 3 repetitions of the back squat at 91% of one-repetition maximum (1RM). Concordantly, Seitz, de Villarreal and Haff (2014) reported a better performance in 20m sprint time after subjects perform 3 repetitions of back squat with load of 90% of 1RM. These were some interesting results that call for attention by the coaches and the researchers.

The common exercises used to elicit PAP used heavy-load (higher than 75% 1RM) resistance exercises (Kilduff et al., 2008). Nevertheless, the use of high external loads in the real competition context is difficult and non-practical. As alternative, recent studies focused on the assessment of ballistic exercises during warm-up. These investigations found some benefits by using depth jumping during the warm-up protocol to both maximal strength (Masamoto, Larsen, Gates & Faigenbaum, 2003), sprint performance (Till & Cooke, 2009) and vertical jump (Stieg et al., 2011; Till & Cooke, 2009). In fact, the ballistic exercises recruited type II motor units (Turner, Bellhouse, Kilduff & Russell, 2015) and caused some PAP phenomenon. However, research is not consensual and the results still not clear on the benefits of including these practices in a typical warm-up. In addition, the effects on performance and also in biomechanical and physiological responses, are yet to be determined.

Therefore, it was hypothesized that a warm-up including ballistic exercises would improve 30m running performance, by changing the stride parameters (stride length (SL) and stride frequency (SF)) and physiological response. The primary aim of the current study was to verify the acute effects of a warm-up including ballistic exercises inducing a PAP, easy to apply on a real competition context, on 30m running performance. In addition, a second 30m trial was assessed to better understand the warm-up effects during competition and training. This second repetition would be important to understand the neuromuscular and metabolic responses, helping to develop optimized training strategies. Repeated efforts have been associated with neuromuscular and metabolic factors that influence performance (Spencer, Bishop, Dawson & Goodman, 2005; Taylor, Weston & Portas, 2013). The primary outcomes for our study were the 30m running performance (time) and biomechanical variables (SL and SF). Secondary outcomes included physiological (blood lactate concentration: [La$^-$], tympanic temperature: Tymp T and heart rate: HR) and psychophysiological (ratings of perceived exertion (RPE)) variables.

Material and methods

Participants

Twenty-two men aged 18-22 years (mean ± SD: 19.32 ± 1.43 years of age, 1.76 ± 0.07m of height, 68.48 ± 9.91 kg of body mass) volunteered to participated in the current study. Participants were physically active sport science students and were included on the basis that they were healthy, injury free, and engaged in physical activity regularly with an experience of running and testing for the last 2 years, although they were not competitive sprinters. Each individual was asked to report any previous illness, injury or other physical issue that would hinder their performance. Criteria of exclusion from the study was the evidence of any medical or orthopedic problem, a self-reported fitness classification below moderately active, or any other self-reported issue that would endanger their own health. After local ethics board approval, ensuring compliance with the Declaration of Helsinki, the subjects were informed about the study procedures, and a written informed consent was signed.

Design

The purpose of the present study was to evaluate the effects of typical warm-up procedures (WU), the inclusion of PAP and no warm-up (NWU) on 30m running performance, analyzing biomechanical, physiological and psychophysiological variables.

Each participant completed two 30m run time-trials after each warm-up condition, in a randomized order, separated by 48h. The WU design was based on literature recommendations (Taylor, Weston & Portas, 2013; Zois, Bishop, Ball & Aughe, 2011) and involved a low intensity aerobic component followed by specific running tasks. The PAP warm-up included lower body ballistic exercises according to previous suggestions (Maloney, Turner & Fletcher, 2014) after completing WU. During the NWU condition, the subjects were asked not to perform any type of action or movement that could function as a warm-up prior to the 30m sprint, remaining seated for 5 minutes.

Experimental Procedures

All the procedures took place at the same time of the day (14:00 – 18:00 PM) for each participant under the same environmental conditions (~20°C air temperature and ~60% of humidity) in a sport facility. The participants were familiarized with the warm-up procedures 72 hours before the experiments, and they were reminded to maintain the same training, recovery, and diet routines during the assessment days, avoiding strenuous exercise, and abstaining from consuming caffeine 48 hours before testing.

After arriving, each participant remained seated for 5min to rest, concentrate on the procedures, and baseline measurements of HR (Vantage NV; Polar, Kempele, Finland), Tymp T (Thermoscan IRT 4520; Braun, Kronberg, Germany), and [La-] (Lactate Pro LT 1710; Arkray Inc., Kyoto, Japan) were then assessed. Then, each volunteer was then randomly assigned to a warm-up protocol (Figure 1).

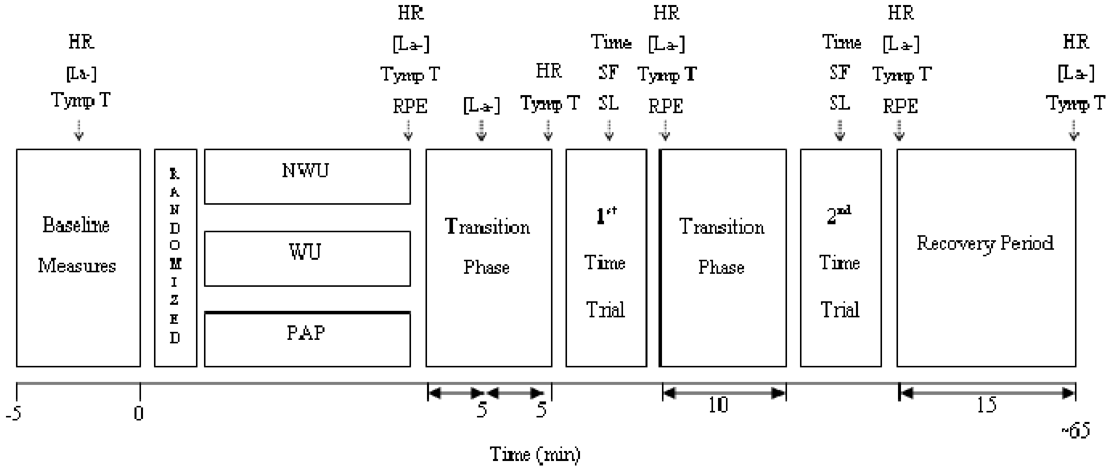

Figure 1. Schematic representation of the study design and testing procedures used. NWU = no warm-up; WU = typical warm-up. PAP = WU with inclusion of post-activation potentiation exercitation. HR = heart rate. [La-] = blood lactate concentration. TympT = tympanic temperature. SF = stride frequency. SL = stride length. RPE = ratings of perceived exertion.

Warm-up Protocols

The warm-ups were designed based on recent researches (Silva et al., 2018; Taylor et al., 2013; Zois et al., 2011) and with the help of an experienced coach. The main difference between the warm-ups were the inclusion of lower-body ballistic exercises to stimulate PAP.

The ballistic exercises are characterized by movements performed with maximal velocity and by the acceleration of a mass throughout the movement (Maloney, Turner & Fletcher, 2014). In these movements the braking phase of the exercise is reduced, and the relative duration of positive acceleration is increased, facilitating the force output and muscle activation (Maloney et al., 2014). The ballistic exercises usually include different types of throws and jumps, and among these, either depth jumps, or weighted jumps are suggested to be the most effective strategies (Maloney et al., 2014). WU comprised 5min of easy run (lower than 65% of estimated maximal HR), followed by eight exercise drills, such as rhythmic jumps from foot to foot (2 exercises), ankle drills (2 exercises), skipping drills (2 exercises), high-knee running (2 exercises). These exercise drills were performed over a 20 m distance (10s of recovery between) and all the participants performed the same exercises, that were repeated in both protocols. Then, 2x40m running at gradually increasing intensity were performed. In the PAP condition, the participants performed the WU followed by 2 sets of 5 depth jumps from a box of 70 cm height (3minutes of recovery between the sets) as previously suggested by Maloney et al. (2014). Each jump was performed by stepping off a box with one foot, landing with bent knees, then immediately jumping with maximal effort. The subjects were instructed to jump as quick and high as possible. The subjects had to keep their hands on their hips to eliminate any contribution of arm swing (Andrade et al., 2015; Byrne, Kenny & O'Rourke, 2014).

Time-trial performance

Once the participants finished warming-up, they remained seated for 10min before performing the 30m time-trials. In NWU condition the participants did not perform any exercise before time-trial and remained seated. The subjects started from a standing position with the trunk bent forward and the lower limbs apart and slightly bent, positioned behind the starting line. After official commands, each participant started maximal running using a standing start with the lead-off foot placed 1m behind the first timing gate. Times were measured by Photocell timing gates (Brower photocells, Wireless Sprint System, USA) placed at 0, 15, and 30m so that the times needed to cover 0–15m (T0-15), 15–30 m (T15-30) and 0-30m (T30) could be determined. After 10min rest, the subjects performed a second 30m sprint. Strong verbal encouragement was provided during all tests to motivate participants to give a maximal effort.

Kinematics

All the procedures were recorded by two video cameras (Casio Exilim Ex-F1, f=30Hz) placed perpendicular to the running track. This enabled the acquisition of basic kinematic data such as the number of strides performed by each subject, the average SL and average SF calculations, between 0 and 15m and between 15 and 30m, using an open-source software (Kinovea, version 0.8.15). In running, a stride is defined as the time between two consecutive specific discrete events, normally defined as two consecutive foot strikes on the same foot. SL is defined as the distance traveled during a stride and SF is defined as the rate of strides per min. SF was converted to International System Units (Hz) for further analysis. Knowing the time performed and thus the running velocity, SL was determined from the division of running velocity by SF (Hamill & Knutzen, 2009; Hunter, Marshall & McNair, 2004).

Physiological and Psychophysiological Variables

Capillary blood samples for [La-] assessment were collected from the fingertips before and 5min after warm-ups, and 5min after each 30m sprint to obtain the highest value ([La-]peak) (Goodwin, Harris, Hernández & Gladden, 2007), and after 15min of recovery. HR and Tymp T were assessed before and after each warm-up (5min) before the trial (9th min) immediately after each time-trial (1min) and after 15min of recovery. Additionally, the RPE were recorded using a 10-points Borg scale modified (Foster et al., 2001) after warm-ups and after the time-trials.

Statistical Analysis

Standard statistical methods were used for the calculation of mean ± SD, and 95% confidence intervals for all variables. The normality of all distributions was verified using Shapiro-Wilk tests. Data for all variables analysed were homogeneous and normally distributed. Considering our primary aim, the effect of the warm-up was analyzed by comparing each single variable (dependent variables) between the three conditions (NWU, WU, and PAP) using an ANOVA for repeated measures (independent variable: warm-up conditions). The sphericity was checked using Mauchly's test and when the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse-Geisser procedure. Bonferroni post-hoc analysis were performed to further investigate the effect of each condition. All these statistical procedures were performed using IBM SPSS Statistics for Windows®, version 22.0. (Armonk, NY, USA: IBM Corp.) and the level of statistical significance was set at $p \leq 0.05$. In addition, the effect size was calculated to estimate variance between conditions (partial eta squared: η_p^2) and Hedges'g (effect size: ES) for within-subjects' comparisons using the Excel spreadsheet by Lakens (2013). ES values of 0.20, 0.60, 1.20 and 2.00 were considered small, moderate, large and very large magnitudes, respectively ((Hopkins, Marshall, Batterham & Hanin, 2009). For η_p^2, cut-off values were interpreted as 0.01 for small, 0.09 for moderate and 0.25 for large.

Results

Baseline measures

Before warm-up, the physiological variables were not different between conditions. Baseline measurements of Tymp T (NWU: 36.6 ± 0.3°C vs. WU: 36.6 ± 0.5°C vs. PAP: 36.7 ± 0.3°C; *F* = 0.43, p = 0.58, $\eta_p^2 = 0.02$), HR (79 ± 7 bpm vs. 78 ± 7 bpm vs. 79 ± 5 bpm; *F* = 1.20, p = 0.31, $\eta_p^2 = 0.05$) and [La$^-$] (1.6 ± 0.5 mmol·L^{-1}vs. 1.6 ± 0.5 mmol·L^{-1} vs. 1.6 ± 0.5 mmol·L^{-1}; *F* = 1.20, p = 0.31, $\eta_p^2 = 0.05$) were similar between the three conditions.

Acute effects of different types of warm-up stimuli

Table 1 presents a comparison between the HR, the Tymp T, the [La$^-$] immediately after the warm-ups. It is possible to verify significant differences in HR (*F* = 19.37, p < 0.01, η_p^2= 0.48) and [La-] (*F* = 2425.55, p < 0.01, η_p^2= 0.99), with higher values for either warm-ups compared with no warm-up condition. No significant differences were found between conditions in Tymp T (*F* = 0.41, p = 0.67, η_p^2= 0.02). Moreover, RPE values after both warm-ups were not different (WU: 3.86 ± 1.36 vs. PAP: 3.82 ± 1.18; p = 0.89, ES = 0.03).

Table 1. Mean ± SD values (95% confidence interval) of physiological after performing the typical warm-up (WU), the post-activation potentiation warm-up (PAP) and at baseline (NWU) (n=22).

	NWU	WU	PAP	NWU vs WU		NWU vs PAP		WU vs PAP	
				p-value	ES	p-value	ES	p-value	ES
HR	79 ± 7	94 ± 13	92 ± 9	**<0.01****	1.45	**<0.01****	1.69	0.53	0.15
[bpm]	(76, 81)	(89, 99)	(89, 96)						
[La$^-$]	1.6 ± 0.5	3.6 ± 1.5	2.2 ± 1.1	**<0.01****	1.74	**0.01***	0.67	**<0.01****	0.99
[mmol·L^{-1}]	(1.4, 1.8)	(3.0, 4.2)	(1.8, 2.7)						
Tympanic T	36.6 ± 0.3	36.7 ± 0.4	36.6± 0.3	0.45	0.25	0.68	0.14	0.54	0.11
[°C]	(36.5, 36.7)	(36.5, 36.8)	(36.5, 36.8)						

Mean ± SDvalues (95% confidence limits). HR = heart rate. [La$^-$] = blood lactate concentration. Tympanic T = tympanic temperature. * p≤0.05; **p≤0.01

Time-trials performances

Table 2 presents the results recorded in the first 30m sprint after NWU, WU and PAP. Moderate differences were found between the NWU and WU conditions assessed ($F = 2.56$, $p = 0.07$, $\eta_p^2 = 0.12$) in the 30m sprint. The participants were 1.93% and 0.64% faster after the WU and PAP, compared to NWU, respectively. Moreover, fourteen of them were faster after WU and eight were faster after PAP.

The warm-ups assessed resulted in large effect in the SL during the second 15m ($F = 2.78$, $p = 0.07$, $\eta_p^2 = 0.12$) and moderate effect in the SF ($F = 0.81$, $p = 0.45$, $\eta_p^2 = 0.04$). After the trial, the physiological responses showed to be different regarding the [La-] ($F = 5.57$, $p = 0.01$, $\eta_p^2 = 0.21$) and the RPE values ($F = 5.32$, $p = 0.01$, $\eta_p^2 = 0.20$), and no significant differences were found in HR ($F = 1.98$, $p = 0.17$, $\eta_p^2 = 0.09$) and Tymp T($F = 0.01$, $p = 0.99$, $\eta_p^2 = 0.00$).

Table 2 - Mean ± SD values of the first 30-m time trial, biomechanical and physiological variables assessed during experimental protocols: no-warm-up (NWU), typical warm-up (WU) and WU complemented with ballistic exercises (PAP) (n=22).

	NWU	WU	PAP	NWU vs WU		NWU vs PAP		WU vs PAP	
				p-value	ES	p-value	ES	p-value	ES
T0-15 [s]	2.72 ± 0.10	2.67 ± 0.10	2.69 ± 0.15	**0.03***	0.48	0.45	0.23	0.33	0.15
	(2.67, 2.76)	(2.63, 2.71)	(2.63, 2.76)						
T15-30 [s]	1.95 ± 0.12	1.92 ± 0.12	1.94 ± 0.12	0.14	0.24	0.63	0.08	0.13	0.16
	(1.90, 2.00)	(1.87, 1.96)	(1.90, 1.99)						
T30 [s]	4.67 ± 0.20	4.58 ± 0.20	4.64 ± 0.25	**0.03***	0.43	0.44	0.13	0.13	0.26
	(4.58, 4.75)	(4.50, 4.67)	(4.53, 4.74)						
T0-15 SF [Hz]	2.07 ± 0.14	2.10 ± 0.13	2.09 ± 0.18	0.20	0.21	0.66	0.12	0.58	0.06
	(2.01, 2.13)	(2.05, 2.16)	(2.01, 2.16)						
T15-30 SF [Hz]	2.21 ± 0.16	2.19 ± 0.19	2.17 ± 0.15	0.51	0.11	0.23	0.25	0.54	0.11
	(2.15, 2.28)	(2.11, 2.27)	(2.10, 2.23)						
T0-15 SL [m]	2.68 ± 0.14	2.69 ± 0.13	2.69 ± 0.16	0.88	0.07	0.86	0.06	0.93	0.00
	(2.62, 2.74)	(2.63, 2.74)	(2.62, 2.75)						
T15-30 SL [m]	3.49 ± 0.19	3.60 ± 0.25	3.58 ± 0.23	**0.02***	0.48	0.14	0.41	0.64	0.08
	(3.41, 3.57)	(3.50, 3.71)	(3.49, 3.67)						
HR [bpm]	126 ± 17	134 ± 18	132± 12	0.13	0.46	0.19	0.38	0.40	0.16
	(119, 133)	(127, 142)	(127, 137)						
$[La^-]_{peak}$ [mmol·L^{-1}]	3.9 ± 1.1	5.0 ± 1.6	4.0 ± 1.0	**0.01****	0.79	0.711	0.10	**0.02***	0.75
	(3.4, 4.3)	(4.3, 5.6)	(3.6, 4.4)						
Tympanic T [ºC]	36.5 ± 0.4	36.5 ± 0.4	36.5 ± 0.3	0.90	0.02	0.90	0.03	1.00	0.00
	(36.4, 36.7)	(36.4, 36.7)	(36.4, 36.7)						
RPE	2.77 ± 1.23	3.59 ± 1.59	3.55 ± 1.14	**0.02***	0.56	**<0.01****	0.63	0.87	0.03
	(2.26, 3.29)	(2.93, 4.26)	(3.07, 4.02)						

Mean ± SD values (95% confidence limits). SF = stride frequency. SL = stride length. HR = heart rate. $[La^-]_{peak}$ = peak values of blood lactate concentration. Tympanic T = tympanic temperature. RPE = ratings of perceived exertion. * p≤0.05; **p≤0.01

In the second 30m sprint (Table 3), moderate differences were found between conditions (*F* = 1.56, p = 0.23, η_p^2= 0.07), with higher performances after WU compared to PAP. There was a 1.28% improvement from the first to the second sprint of 30 m in the NWU condition, a 0.44% improvement in the WU condition and a 0.22% in the PAP condition. The different responses to each warm-up condition in the 30m time trials can be easily confirmed in Figure 2.

No significant differences were found in running kinematics during the second sprint, specifically regarding the SF in the first (*F* = 0.06, p = 0.90, η_p^2 = 0.00) and second 15m (*F* = 1.33, p = 0.27, η_p^2 = 0.06), and the SL in the first (*F* = 0.87, p = 0.43, η_p^2 = 0.04) and second 15m (*F* = 0.16, p = 0.85, η_p^2 = 0.01). After this second trial, HR were largely (*F* = 7.23, p = 0.00, η_p^2= 0.26) and RPE were moderately (*F* = 2.87, p = 0.07, η_p^2= 0.12) different between conditions, with the highest values found in either WU and PAP. The [La-] (*F* = 3.92, p = 0.03, η_p^2= 0.16) was higher after WU compared with NWU, while no significant differences were found in Tymp T (*F* = 1.20, p = 0.30, η_p^2= 0.05).

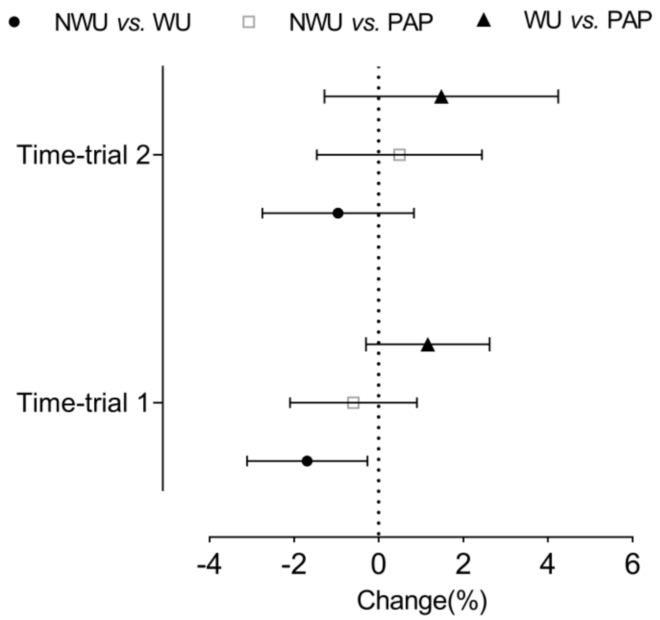

Figure 2. Mean changes (± 90% CI) verified between conditions, specifically no warm-up (NWU), after typical warm-up (WU) and after WU complemented with ballistic exercises (PAP) in each 30m time-trial.

Table 3 - Mean ± SD values of the second 30-m time trial, biomechanical and physiological variables assessed during experimental protocols: no-warm-up (NWU), typical warm-up (WU) and WU complemented with ballistic exercises (PAP) (n=22).

	NWU	WU	PAP	NWU vs WU		NWU vs PAP		WU vs PAP	
				p-value	ES	p-value	ES	p-value	ES
T0-15 [s]	2.69 ± 0.16	2.65 ± 0.13	2.68 ± 0.15	0.35	0.26	0.80	0.06	0.20	0.21
	(2.62, 2.76)	(2.60, 2.71)	(2.61, 2.74)						
T15-30 [s]	1.92 ± 0.11	1.91 ± 0.10	1.95 ± 0.12	0.35	0.09	0.05	0.25	**0.01****	0.35
	(1.87, 1.96)	(1.86, 1.95)	(1.90, 2.00)						
T30 [s]	4.61 ± 0.23	4.56 ± 0.22	4.63 ± 0.26	0.27	0.21	0.69	0.08	**0.02***	0.28
	(4.51, 4.71)	(4.47, 4.65)	(4.52, 4.74)						
T0-15 SF [Hz]	2.09 ± 0.19	2.08 ± 0.10	2.09 ± 0.17	0.76	0.06	0.87	0.00	0.82	0.07
	(2.01, 2.17)	(2.04, 2.12)	(2.02, 2.15)						
T15-30 SF [Hz]	2.22 ± 0.17	2.21 ± 0.14	2.17 ± 0.16	0.82	0.06	0.25	0.29	0.13	0.26
	(2.14, 2.29)	(2.15, 2.27)	(2.10, 2.23)						
T0-15 SL [m]	2.69 ± 0.17	2.73 ± 0.10	2.70 ± 0.15	0.19	0.28	0.72	0.06	0.28	0.23
	(2.62, 2.76)	(2.69, 2.78)	(2.64, 2.77)						
T15-30 SL [m]	3.55 ± 0.23	3.58 ± 0.20	3.58 ± 0.18	0.61	0.13	0.69	0.14	0.96	0.00
	(3.46, 3.65)	(3.50, 3.66)	(3.50, 3.65)						
HR [bpm]	128 ± 16	142 ± 18	144± 13	**<0.01****	0.76	**<0.01****	1.02	0.70	0.12
	(122, 135)	(134, 149)	(138, 149)						
$[La^{-}]_{peak}$ [mmol·L^{-1}]	4.5 ± 1.3	5.5 ± 1.7	4.8 ± 1.4	**0.01***	0.68	0.34	0.26	0.10	0.44
	(3.9, 5.0)	(4.8, 6.3)	(4.3, 5.4)						
Tympanic T [ºC]	36.4 ± 0.3	36.5 ± 0.4	36.4 ± 0.4	0.14	0.28	0.72	0.11	0.17	0.37
	(36.3, 36.6)	(36.4, 36.7)	(36.2, 36.6)						
RPE	3.18 ± 1.10	3.82 ± 1.26	3.64 ± 1.18	0.06	0.52	**0.04***	0.39	0.53	0.14
	(2.72, 3.64)	(3.29, 4.34)	(3.14, 4.13)						

Mean ± SD values (95% confidence limits). SF = stride frequency. SL = stride length. HR = heart rate. $[La^{-}]_{peak}$ = peak values of blood lactate concentration. Tympanic T = tympanic temperature. RPE = ratings of perceived exertion. * p≤0.05; **p≤0.01

Differences were found after 15 minutes of recovery in the HR ($F = 13.74$, p = 0.00, $\eta_p^2 = 0.40$) with higher values in the WU (102 ± 10 bpm) and in the PAP (105 ± 10 bpm) compared with NWU (93 ± 11 bpm; p = 0.00, ES = 0.81 and p = 0.00, ES = 1.02, respectively). On the other hand no differences were found in the [La-] values (3.3 ± 1.1 vs. 3.4 ± 1.1 vs. 3.0 ± 1.2 $mmol{\cdot}L^{-1}$; $F = 1.24$, p = 0.30, $\eta_p^2 = 0.06$) and Tymp T (36.6 ± 0.3 vs. 36.7 ± 0.4 vs. 36.5 ± 0.4ºC; $F = 1.88$, p = 0.17, $\eta_p^2 = 0.08$).

Discussion

The main purpose of the current study was to verify the acute effects of a warm-up including ballistic exercises inducing a PAP effect, easy to apply on a real competition context, in 30m sprint performance. The main results confirmed an increased 30m running performance after WU compared with NWU condition. Nevertheless, no differences were found between the inclusion or not of ballistic exercises during warm-up. The performance improvement in WU was probably caused by a faster initial meters (0-15m) and increased SL in the second half (15-30m) of the time-trial. These better performances resulted in increased [La^-] after the time-trial as well as higher RPE. Our results suggested that WU optimized short sprint performances and adding ballistic exercises did not additionally improve those performances.

These results agree with the beneficial effects of WU for running sprints suggested by literature (Andrade et al., 2015; McGowan et al., 2015; Taylor et al., 2013). Previous research found that running sprint performance can be enhanced by between 1 and 5% after warm-up (McGowan et al., 2015). Accordingly, in the current study, the statistical analysis only found significant differences between WU and NWU. However, it should be noted that there were eight subjects that settled their best time after PAP. These unclear results were already evidenced by previous researches. While some studies verified that a brief warm-up of 5 minutes of running, dynamic stretches and three vertical jumps resulted in 5% better performance in 20m sprint compared to the warm-up without the jumps (Byrne et al., 2014), others found no differences in 20m sprint when adding different PAP strategies to usual warm-up, such as deadlifts, tuck jumps or isometric maximum voluntary knee extensions (Till & Cooke, 2009).

The use of ballistic exercises during warm-up hass been suggested to stimulate subsequent performance in short-term maximal efforts (Hodgson, Docherty & Robbins, 2005; Seitz et al., 2014), however, this did not happen in the current study. No differences were found in the first 30m time-trial and in the second 30m sprint time-trial the difference between WU and PAP increased, with clear better performances for WU condition. Although there is a great interest on the effects of PAP warm-up on sports performance, some studies have been unsuccessful in evidence of their importance for sprint performance (Lima et al., 2014; Smith et al., 2014). Inconsistencies between studies and non-beneficial effects of including PAP strategies during warm-up have been attributed to differences in conditioning level and muscle fiber composition of the subjects, intensity of the PAP warm-up, and/or recovery time between PAP warm-up and the following high-intensity exercise (Bevan et al., 2010; Smith et al., 2014). Also, the lack of specificity of the jumps and/or an insufficient load to stimulate some higher responses in PAP could be pointed as reasons for unclear results.

Regarding the biomechanical variables assessed, our results indicated that warm-up seems to influence performance sprint through a significance increase in SL in last 15m of the first time-trial. Bezodis, Irwin, Kuntze and Kerwin (2011) suggested that the velocity of elite sprinters can be individually dependent on the SL and the SF, with pre-sprint exercises establishing an important role for adjusting the SL and the SF. The runners adjust the SL and the SF to get the most efficient running, optimizing velocity (Salo, Bezodis, Batterham & Kerwin, 2011). In the current study, the participants were faster in WU in the beginning and then were able to maintain high values of SL in the final 15m, confirming previous studies that suggested that there is a biomechanical adaptation in response to different warm-up procedures (Neiva et al., 2015; Neiva et al., 2017b).

In the current study, the warm-up procedures caused the physiological variables to increase, regarding the HR and [La$^-$] values after warm-up, and within the range of values that some authors suggested to be adequate for a proper warm-up (Neiva et al., 2017b; Raccuglia et al., 2016, Zourdos et al., 2016). This could explain the better response in the first sprint after either warm-up procedures. Interestingly, no differences were found in Tymp T. Literature tends to report that warm-up is usually intended to generate muscle and body temperature increase that allows several internal changes (Bishop, 2003; McGowan et al., 2015). Considering that the best sprint was performed after WU and the main differences were found in HR and [La$^-$] but not in Tymp T, this could reveal that active warm-up caused internal changes that are essential to optimize short running performance, rather than augmented temperature, and agreeing with previous recommendations (McGowan et al 2015; Silva et al. 2018). Nevertheless, we should not disregard that this similar Tymp T could be resultant from the rapid response of the body trying to cool itself to maintain homeostasis and the incapacity of the Tymp T evaluation to measure these changes instantly.

The recovery period also highlights the importance of warm-up procedures, with and without performing ballistic exercises. After 15 minutes of recovery, the HR was found to be higher in WU and in PAP compared with NWU. There are reports in the literature that the increased HR lead to an increased blood flow to the working muscles (Lopez, Smoliga & Zavorsky, 2014; Toubekis et al., 2008) and this could function as immediate recovery from previous efforts. In fact, this is believed to enhance lactate removal by allowing a faster distribution to the sites of removal. So, the increased HR during this period could contribute to a faster recovery response in warm-ups conditions.

Some limitations should be addressed to the current study. We should be aware of the possible negative influence of adding ballistic exercises to warm-up, because of increased load. In the current study, the perceived effort after warm-ups were not different between warm-ups and thus evidencing the same level fatigue perception in both WU and PAP. HR values were also not different between conditions and the [La-], despite different between WU and PAP, were considered very low intensity and it might suggest that the ballistic exercises used were not enough to induce extra physiological stress. This could be caused by some lack of specificity of the ballistic exercises used and/or the possible individualized effect of PAP stimulation (Hodgson et al., 2005; Seitz et al., 2014; Xenofondos et al., 2010), that should be investigated. Moreover, the current results should be interpreted knowing that the participants were not sprinting specialists/athletes and so, cannot be entirely extrapolated higher-skilled sprinters during official events. It is known that PAP could be influenced by training levels (Xenofondos et al., 2010). Future studies should include a larger number of participants and include females to clarify some of the analyzed findings. However, we took several steps to strengthen our statistical analysis as described in the statistical section. The current findings still relevant for coaches and researchers for increased knowledge on warm-up and the effects on performance. Future research should investigate different PAP strategies (e.g. combining different jumps or short-term sprints) and different recovery times between the warm-up and the race. Moreover, other evaluation methods could be used to complement our measures and to deepen our findings, such as muscle temperature and other biomechanical variables.

Conclusion

In conclusion, the results showed that 30m running is influenced positively by warm-up procedures, supported by the best results obtained after the WU. Moreover, the performance improvement in WU was probably caused by a faster beginning (0-15m) and increased SL in the second half (15-30m) of the time-trial. Our results did not confirm our original hypothesis, evidencing a lack of additional positive effects from the PAP condition. No differences were found between WU and PAP but several participants performed their better 30m sprint when included ballistic exercises during warm-up, highlighting an individual response regarding short distance performances.

Practical applications

It is clear that sprinters should warm-up for better competitive and training performances in short distances. Coaches and researchers should be aware that strategy and running technique during short sprints is influenced by warm-up. Moreover, the current study highlights the need for tailored and customized warm-up designs and specifically PAP strategies during warm-up, because participants had different individual responses.

Study 4

The effect of warm-up running technique on sprint performance

Abstract

The purpose of the current study was to analyze the effect of changing the running technique during warm-up on sprint performances, running biomechanics, physiological and psychophysiological responses. Thirty-one physically active men aged 18-23 years (mean ± *SD*: 19.35 ± 1.08 years of age; 1.77 ± 0.07 m of height; 71.90 ± 10.37 kg of body mass) volunteered to participate and randomly performed two maximal 30m sprints, 5min after completing a warm-up focused on increased stride length-SL(WUL) or a warm-up focused on increased stride frequency-SF (WUF). The results showed that there were no differences between the 30m sprint performances and in running biomechanics. However, WUF showed increased performances in the first 15 m of the race (WUF: 2.59 ± 0.11s vs. WUL: 2.63 ± 0.15s; p = 0.03) and WUL resulted in higher performances in the last 15m (1.94 ± 0.19s vs. 1.88 ± 0.09s; p = 0.05). In the second 30m time-trial, WUF also resulted in faster starting 15m of the race (2.58 ± 0.12s vs. 2.63 ± 0.16s; p=0.04). Interestingly, the WUF was the warm-up that revealed more stability in performances and running biomechanics between both trials. These results showed that there were no significant differences between warm-ups comprising exercises focusing in higher SL or higher SF in 30m sprint biomechanics and performance. Nevertheless, different running strategies were caused by those two warm-ups and a more stabilized running pattern and performance values were found when warm-up focused on higher SF.

Key-Words: Pre-exercise; Running, Stride length; Stride frequency, Repeated-sprints

Introduction

The warm-up has been suggested to increase preparedness for subsequent effort, optimizing performance and reducing the risk of injury (McGowan, Pyne, Thompson & Rattray, 2015; Silva, Neiva, Marques, Izquierdo & Marinho, 2018). Most mechanisms of warm-up were associated with the temperature change (Kilduff, West, Williams & Cook, 2014), stimulating the muscle contraction and the efficiency of the metabolic reactions (Kilduff et al., 2014; Swanson, 2006). Furthermore, it is known that warm-up could facilitate joint range of movement, increase blood flow and help to efficiently produce strength and power, being determinant in most sports (Taylor, Weston & Portas, 2013). To achieve those changes, different practices are usually recommended before a running race event, despite little scientific evidence on the specific warm-up structure is available (Gil, Neiva, Sousa, Marques & Marinho, 2019b; McGowan et al., 2015).

Specifically, in running, the typical warm-up included a brief period (5 to 10min) of low intensity running and stretching exercises, followed by specific exercises (Gil et al., 2019b; McGowan et al., 2015; Zois, Bishop, Ball & Aughey, 2011). Recent studies reported positive effects of a typical warm-up in short and long running distances (McGowan et al., 2015; Silva et al., 2018). However, there is still a lot to know on the specific exercises to be used.There are some evidences on the use of race-pace or near race-pace sets, that resulted in improved 60m and 800m running performances (Ingham, Fudge, Pringle & Jones, 2013; Watterdal, 2013). Moreover, post-activation potentiation strategies, such as few repetitions of back squats (Byrne, Kenny & O'Rourke, 2014; Lim & Kong 2013; Rønnestad & Ellefsen, 2011) with high external loads, or few drop jumps, showed to improve 20 and 60m performances by approximately 2 to 5%. Some doubts still exist on the use of these recent trends of warm-up specific exercises, with some studies showing no benefits of using either of the aforementioned exercises (Gil et al., 2019a; Gil et al., 2019b; McGowan et al., 2015).

Recently some researchers highlighted other gains that could emerge from the warm-up, such as the possibility of learning for the sensorimotor activity and acute motor changes during warm-up (Ajemian, D'Ausilio, Moorman & Bizzi, 2010; Neiva et al., 2017). Ajemian et al. (2010) were the first to suggest that warm-up induces the recalibration of the sensorimotor network of the athletes and restores their skills to a finely tuned state. Later, Neiva et al. (2017) verified that there was an acute response of freestyle swimming technical pattern according to the specific exercise focusing on higher stroke length or stroke frequency during warm-up. The swimmers replicated the motor skills focused on warm-up during the initial meters of the race. To our knowledge, this was never assessed in running. It is known that running performances depends on the optimal ration between stride length (SL) and stride frequency (SF) to maximal sprinting velocity (Krzysztof & Mero, 2013). SL and SF are conditioned by the neuromuscular regulation of movement (Coh, Milanovic & Kampmiller, 2001; Prampero et al., 2005) and therefore, it can be influenced by specific warm-up tasks.

Most studies in sprinting, focused on performance and physiological variables without the full understanding of the warm-up effects. There is a scarcity of knowledge about the effect of warm-up on the biomechanical variables of running, and that could be critical to training and performance. Therefore, it was hypothesized that sprint pattern will be influenced by the type of warm-up used. Warm-up with higher SF may enhance sprint performance by increased SF, while higher SL during warm-up may enhance sprint performance by increased SL. So, the primary aim was to analyze the effect of manipulating running kinematics (SL and SF) during warm-up in 30m sprinting performance. In addition, a second 30m trial was assessed to better understand the warm-up effects during competition and training. The second repetition is important to understand the neuromuscular and metabolic responses, helping to develop optimized training strategies (Spencer, Bishop, Dawson & Goodman, 2005; Taylor et al., 2013). The primary outcomes were the performance (time) and biomechanical (SL and SF) variables and the secondary outcomes included physiological (blood lactate concentration: [La-]; heart rate: HR; tympanic temperature: Tymp T) and psychophysiological (ratings of perceived exertion: RPE) variables.

Material and methods

Subjects

Thirty-one males aged 18-23 years (mean ± standard deviations: SD): 19.35 ± 1.08 years of age; 1.77 ± 0.07 m of height; 71.90 ± 10.37 kg of body mass) volunteered to participate in the current study. Participants were physically active sport science students, engaged in physical activity regularly with an experience of running and testing for the last two years, although they were not competitive sprinters. Each individual was asked to report any previous illness, injury or other physical issue that would hinder their performance and they were included on the basis that they were healthy and injury free. Criteria of exclusion from the study was the evidence of any medical or orthopedic problem, a self-reported fitness classification below moderately active, or any other self-reported issue that would endanger their own health. The subjects were informed about the study procedures, and a written informed consent was signed. The investigation was conducted in accordance with the Declaration of Helsinki, and was approved by the University of Beira Interior Research Ethics Committee.

Experimental Approach to the Problem

To the best of our knowledge, few studies focused on the effects of using different warm-up tasks on the biomechanical and performance responses in running sprints. Previous studies revealed different adaptations to each condition of warm-up, and changes in SF and SL occurred according to the warm-up performed (Gil et al., 2019a). Considering these changes and knowing that some specific technical adaptations that can occur as response to different warm-up stimulations (Neiva et al., 2017), it was our purpose then to verify the effect of changing the running technique during warm-up on sprint performances, running biomechanics, physiological and psychophysiological responses. For this, each participant completed two experimental sessions (48h interval) that differed in the warm-up performed before the time-trials. Each participant was randomly assigned to a warm-up stimulating SF (WUF) or a warm-up stimulating SL (WUL), followed by 2 maximal 30-m sprints. The dependent variables were time, SF, SL, Tymp T, [La$^-$], HR, and RPE. Physiological and psychophysiological variables were assessed during warm-up, between warm-up and trial, between trials, and during recovery. This design was able to test whether the warm-ups using different technical running stimulations affected running performance.

Procedures

All the procedures took place at the same time of the day (8:00 a.m. – 12:00 p.m.) under the same environmental conditions (~20°C air temperature and ~60% of humidity) at a multi-sport indoor facility (more than 50m long). Moreover, each subject was tested at the same time of the day. The participants were familiarized with the warm-up procedures 72 hours before the experiments, and they were reminded to maintain the same training, recovery, and diet routines during the assessment days, avoiding strenuous exercise 48 hours before testing.

After arriving, each participant remained seated for 5min and baseline measurements of HR (Vantage NV; Polar, Kempele, Finland), Tymp T (Braun Thermoscan IRT 4520, Kronberg, Germany), and [La-] (Lactate Pro LT 1710; Arkray Inc., Kyoto, Japan) were carried-out. Each volunteer was then randomly assigned to a warm-up protocol (Figure 1).

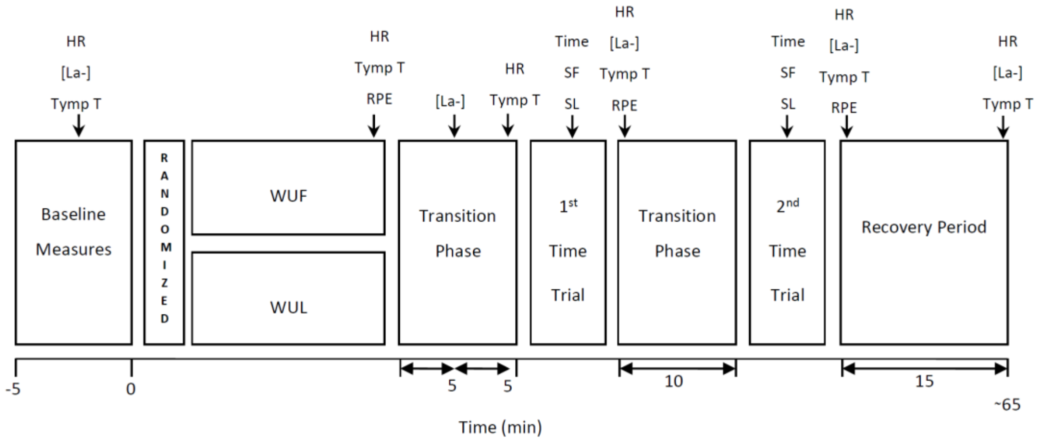

Figure 1. Schematic representation of the study design and testing procedures used. WUF = warm-up stimulating stride frequency; WUL = warm-up stimulating stride length; HR = heart rate; [La$^-$] = blood lactate concentration; Tymp T = tympanic temperature; SF = stride frequency; SL = stride length; RPE = ratings of perceived exertion.

Warm-up Protocols

The warm-ups were designed based on suggestions from previous studies (McGowan et al., 2015; Silva et al., 2018) and with the support of an experienced coach. The main difference between protocols were the technical focus during the main task, with one focusing on the SL and the other on the SF. Both consisted of 5min of easy run (lower than 65% of estimated maximal HR), four exercise drills (2x20m): i) rhythmic jumps from foot to foot; ii) ankle drill; iii) skipping's drills; iv) high-knee running; run demarcated by flags between steps (0.30m in SF and 1.40m in SL). Then, these technical exercises were followed by 2x40-m running at gradually increasing intensity, performed with maximal (measured steps, mean ± SD: 69 ± 3) or minimal number of steps (measured steps, mean ± SD: 16 ± 1), depending on SF or SL focus of warm-up.

Time-trial performance

Once the participants finished the warm-up, they remained seated for 10 min before performing the time-trials. Times were measured by Photocell timing gates (Brower photocells, Wireless Sprint System, Draper, Utah, USA), placed at 0, 15 and 30 m so that the times (seconds and hundredths of second) needed to cover 0-15m (T0-15), 15-30m (T15-30), and 0-30m (T30) could be determined. After official commands, each participant started maximal running using a standing start with the lead-off foot placed 1 m behind the first timing gate. After 10 min of interval, they repeated the 30-m sprint. Strong verbal encouragement was provided during all tests to motivate participants to give a maximal effort.

Biomechanics

All the procedures were recorded by two video cameras (Casio Exilim Ex-F1, Tokyo, Japan; f=30Hz) placed perpendicular to the area that was filmed, in the multi-sport indoor facility (Gil et al., 2019a; Morouço et al., 2017; Neiva et al., 2017). This enabled the acquisition of data such as the number of strides performed by each subject, the average SL and average SF calculations, between 0 and 15m and between 15 and 30m, using an open-source software (Kinovea, version 0.8.15). In running, a stride is defined as the time between two consecutive specific discrete events, normally defined as two consecutive foot strikes on the same foot (Krzysztof & Mero, 2013). SL is defined as the distance traveled during a stride and SF is defined as the rate of strides per min. SF was converted to International System Units (Hz) for further analysis. Knowing the time performed and thus the running velocity, SL was determined from the division of running velocity by SF (Hamill & Knutzen, 2009; Hunter, Marshall & McNair, 2004).

Physiological and Psychophysiological Variables

Capillary blood samples for [La-] assessment were collected from the fingertips before and 5 minutes after warm-ups, 3 and 6min after each sprint to obtain the highest value ([La-]peak) (Goodwin, Harris, Hernández & Gladden, 2007), and after 15 min of recovery. HR was assessed before (1min) and after each warm-up (1min), immediately after each time-trial (1min) and after 15min of recovery. Additionally, the RPE values were recorded using a 10-points Borg scale modified (Foster et al., 2001) immediately after warm-ups and after the time-trials. Each subject's Tymp T was recorded 1min before and 1min after the warm-up and 1min before and 1min after the trial, and after 15min of recovery. Each subject's Tymp T was verified for 3 times, and the maximal value was recorded. This is a good indicator of brain temperature, which controls body temperature (Nimah, Bshesh, Callahan & Jacobs, 2006).

Statistical Analyses

Standard statistical methods were used for the calculation of mean ± SD, and 95% confidence intervals for all variables. The normality of all distributions was verified using Shapiro-Wilk tests, and parametric statistical analysis was used. To compare the 2 trials, Student's paired t-tests and the level of statistical significance was set at $p \leq 0.05$. Hedges'g (effect size (ES)) for within-subjects' comparisons were calculated using the Excel spreadsheet by Lakens (2013). ES values of 0.20, 0.60, 1.20 and 2.00 were considered small, moderate, large and very large magnitudes, respectively (Hopkins, Marshall, Batterham & Hanin, 2009). The smallest worthwhile effects were also computed to determine the likelihood that the true effect was substantially beneficial (positive), trivial, or harmful (negative). Magnitude-based inferences were categorized as clinical for performance measures and mechanistic for other measures. The threshold value for smallest worthwhile change was set at 0.25% for performance; whereas for the other variables, it was set at 0.2 (Cohen's units). The effect was deemed unclear if it was possibly beneficial (0.25%) with an unacceptable risk of harm (0.5%). For mechanistic inferences, an effect was deemed unclear if the true value could be substantial in both a positive and a negative sense (>5% chance of being positive and negative). Where clear interpretation could be made, probabilities were assessed as presented by Hopkins et al. (2009).

Results

Baseline Measures

Before warm-up, the physiological variables were not different between conditions. Baseline measurements of Tymp T (WUF: 36.4 ± 0.5°C vs. WUL: 36.3 ± 0.3 °C; p = 0.65, ES = 0.13), HR (69 ± 7vs. 70 ± 8 bpm; p = 0.51, ES = 0.05) and [La$^-$] (2.0 ± 0.5 vs. 2.0 ± 0.5mmol·L^{-1}; p = 0.47, ES = 0.02) were similar between the 2 conditions.

Acute effects of different types of warm-up stimuli

The acute responses to the different warm-ups are presented in Table 1. No differences were found in HR, in [La$^-$] and in RPE values after warm-up and pre-trial between warm-ups performed. Despite there were no differences in Tymp T immediately after warm-up, there was a greater increase in this variable from post warm-up momentum to pre-trial in WUL compared to WUF (WUF: -0.05 ± 0.44°C vs. WUL: 0.42 ± 0.24°C, p <0.001, ES = 1.27).

Table 1 - Mean ± SD values of physiological and psychophysiological variables assessed after warm-up (Post) and before trial (Pre-trial) during warm-ups either stimulating stride frequency (WUF) or stimulating stride length (WUL) (n=31). P-values and effect sizes (ES) are also presented.

		WUF	WUL	p-value	ES	Mean %change; 95% CI*	%Chance**	Qualitative inference
HR	Post WU	113 ± 16	115 ± 14	0.68	0.07	1.91 ± 4.48	65/8/27	Unclear
[bpm]	Pre-trial	87 ± 10	90 ± 13	0.25	0.24	3.91 ± 5.35	83/4/13	Unclear
[La$^-$] [mmol·L^{-1}]	Post WU	3.9 ± 1.5	3.8 ± 1.4	0.58	0.11	5.55 ± 15.47	33/2/64	Unclear
Tympanic T	Post WU	36.7 ± 0.3	36.6 ± 0.4	0.40	0.17	-0.35 ± 0.33	0/26/74	Possibly -ive
[°C]	Pre-trial	36.5 ± 0.4	36.8 ± 0.3	<0.01	0.95	0.89 ± 0.42	100/0/0	Most likely +ive
RPE	Post WU	4 ± 1	4 ± 1	0.89	0.02	6.44 ± 14.48	48/3/49	Unclear

90% CI = 90% confidence interval. +ive, -ive = positive and negative changes, respectively. HR = heart rate. [La$^-$] = blood lactate concentration. Tympanic T = tympanic temperature. RPE = ratings of perceived exertion. * where a positive % change equates to an increase in WUL condition. ** presented as positive/trivial/negative.

Time-trials performances

Table 2 presents the results recorded in the first 30m sprint after WUF and WUL. No difference was found between the WUF and WUL conditions assessed in the 30m sprint. However, it was possible to verify that subjects were faster in the first 15m sprint when performed the WUF and they were faster in the second 15m partial in the WUL condition (Table 2). No differences were found in the running biomechanics during the 30m trial, but WUF caused increased HR after the trial. No significant differences were found in [La-], in Tymp T and in RPE values.

Table 2 - Mean ± SD values of the first 30-m time trial, biomechanical and physiological variables assessed during warm-ups either stimulating stride frequency (WUF) or stimulating stride length (WUL) (n=31). P-values and effect sizes (ES) are also presented.

	WUF	WUL	p-value	ES	Mean % change; ± 95% CI*	%Chance**	Qualitative inference
T0-15 [s]	2.59 ± 0.11	2.63 ± 0.15	0.03	0.30	1.92 ± 1.65	97/2/1	Harmful
T15-30 [s]	1.94 ± 0.19	1.88 ± 0.09	0.05	0.39	-2.49 ± 2.40	2/2/97	Harmful
T30 [s]	4.53 ± 0.20	4.52 ± 0.22	0.72	0.05	-0.19 ± 1.20	21/29/50	Unclear
T0-15 SF [Hz]	2.13 ± 0.17	2.10 ± 0.16	0.47	0.18	-0.82 ± 3.74	20/8/72	Unclear
T15-30 SF [Hz]	2.12 ± 0.27	2.16 ± 0.22	0.46	0.16	2.75 ± 4.50	77/6/17	Unclear
T0-15 SL [m]	2.75 ± 0.18	2.73 ± 0.16	0.74	0.11	-0.09 ± 3.16	33/11/56	Unclear
T15-30 SL [m]	3.69 ± 0.30	3.73 ± 0.34	0.62	0.12	1.29 ± 3.57	63/10/27	Unclear
HR [bpm]	136 ± 8	129 ± 8	<0.01	0.85	-4.53 ± 2.47	0/0/100	Most likely -ive
$[La^-]_{peak}$ [$mmol\cdot L^{-1}$]	4.9 ± 1.8	5.0 ± 1.7	0.87	0.04	11.97 ± 16.91	59/2/39	Unclear
Tympanic T [ºC]	36.7 ± 0.4	36.6 ± 0.3	0.49	0.17	-0.15 ± 0.45	4/62/34	Possibly -ive
RPE	5.16 ± 1.21	5.48 ± 0.68	0.21	0.32	14.14 ± 13.67	93/1/6	Unclear

95% CI = 95% confidence interval. +ive, -ive = positive and negative changes, respectively. SF = stride frequency. SL = stride length. HR = heart rate. [La$^-$] = blood lactate concentration. Tympanic T = tympanic temperature. RPE = ratings of perceived exertion. * where a positive % change equates to an increase in WUL condition. **WUL presented as harmful/trivial/beneficial for performance (time) and positive/trivial/negativefor other variables.

In the second 30m sprint (Table 3), no differences were found between WUF and WUL conditions. However, it is also possible to verify that subjects were faster in the first 15m sprint when performed the WUF and they were faster in the second 15m sprint when performed the WUL. No differences were found in SF and SL between both warm-up conditions. After trial, HR responses and the Tymp T showed to be higher in WUF, while no significant differences were found in [La-] and in RPE values (Table 3).

Table 3 - Mean ± SD values of the second 30-m time-trial, biomechanical and physiological variables assessed during warm-ups either stimulating stride frequency (WUF) or stimulating stride length (WUL) (n=31). P-values and effect sizes (ES) are also presented.

	WUF	WUL	p-value	ES	Mean % change; ± 95% CI*	%Chance**	Qualitative inference
T0-15 [s]	2.58 ± 0.12	2.63 ± 0.16	0.04	0.34	2.11 ± 1.94	96/3/2	Very Likely
T15-30 [s]	1.95 ± 0.17	1.90 ± 0.09	0.09	0.36	-2.00 ± 2.64	4/4/92	Likely
T30 [s]	4.53 ± 0.22	4.54 ± 0.23	0.92	0.04	0.15 ± 1.46	41/26/34	Unclear
T0-15 SF [Hz]	2.12 ± 0.14	2.08 ± 0.17	0.28	0.25	-1.56 ± 3.13	10/6/84	Unclear
T15-30 SF [Hz]	2.11 ± 0.23	2.14 ± 0.17	0.52	0.14	2.78 ± 4.95	74/6/20	Unclear
T0-15 SL [m]	2.75 ± 0.14	2.75 ± 0.15	0.98	0.00	0.31 ± 2.83	43/14/43	Unclear
T15-30 SL [m]	3.69 ± 0.27	3.70 ± 0.30	0.82	0.03	1.01 ± 3.93	54/10/37	Unclear
HR [bpm]	143 ± 11	134 ± 7	<0.01	0.95	-5.89 ± 2.80	0/0/100	Most Likely -ive
$[La^-]_{peak}$ [$mmol \cdot L^{-1}$]	5.2 ± 1.8	5.1± 2.2	0.78	0.06	4.84 ± 18.85	25/2/73	Unclear
Tympanic T [ºC]	36.8 ± 0.3	36.6 ± 0.3	0.01	0.58	-0.47 ± 0.33	0/10/90	Likely-ive
RPE	5.84 ± 1.24	5.97 ± 0.95	0.62	0.11	8.45 ± 12.75	76/3/21	Unclear

95% CI = 95% confidence interval. +ive, -ive = positive and negative changes, respectively. SF = stride frequency. SL = stride length. HR = heart rate. $[La^-]$ = blood lactate concentration. Tympanic T = tympanic temperature. RPE = ratings of perceived exertion. * where a positive % change equates to an increase in WUL condition. **WUL presented as harmful/trivial/beneficial for performance (time) and positive/trivial/negative for other variables.

The changes between the first and second time-trial are presented in Figure 2. The performances (T0-15m, T15-30m, T30m) were calculated based on time, which means that higher improvements from the first to the second time-trial correspond to lower values of change, that may even reach negative values. Both warm-ups revealed to allow a good maintenance of performance, SL, and SF between the first and the second sprint. However, the similarity between the first and the second sprint seems to be more evident in the WUF condition, that were always close to zero value. This is especially highlighted by the significant differences (confidence interval range do not contain zero-value) presented by T15-30m changes in WUL, that shows a greater performance loss between the first- and second-time trial.

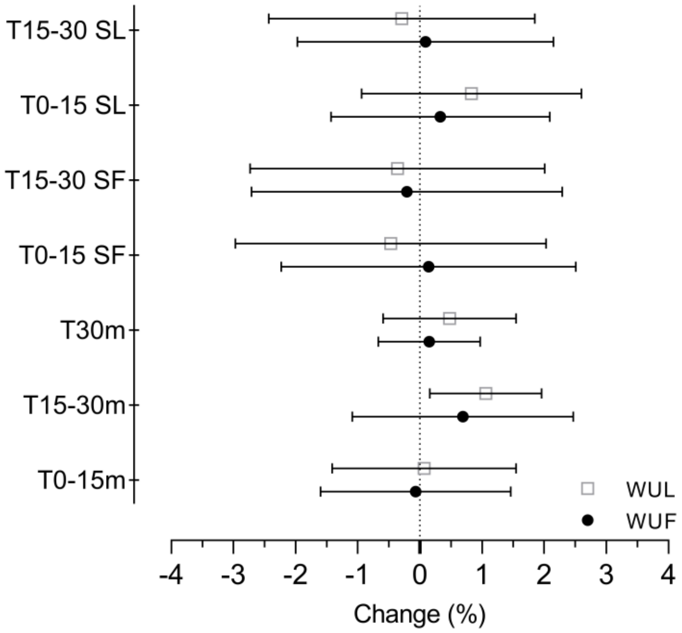

Figure 2. Mean changes (± 95% CI) between the first and second sprints afterwarm-up stimulating stride frequency (WUF) and warm-up stimulating stride length (WUL). SF = stride frequency. SL = stride length.

Conversely, HR showed to be moderately higher in WUL after the 15min of recovery (WUF: 93 ± 9 bpm vs. WUL: 98 ± 9 bpm, p = 0.06, ES = 0.51). No differences were found in the Tymp T (WUF: 36.6 ± 0.3 ºC vs. WUL: 36.7 ± 0.2 ºC, p = 0.24, ES = 0.24), and neither in the [La-] (WUF: 3.3 ± 1.1 mmol·L-1 vs. WUL: 3.1 ± 1.1 mmol·L-1, p = 0.43, ES = 0.18) after recovery.

Discussion

The main purpose of the current study was to analyze the effect of manipulating running biomechanics during the warm-up exercises in 30m running performance. The hypothesis that sprint running pattern would be influenced by the type of warm-up used was not confirmed by the current results, revealing no differences in 30m performance and in running biomechanics. However, the different warm-ups resulted in different 30m sprint strategies, with faster initial meters in WUF condition and faster final meters of the 30m running sprint in WUL. This effect was remained in the second 30m sprint. Moreover, performances and running biomechanics tended to present lower changes between trials in WUF. These results showed that there were no effects of warm-up comprising exercises focusing in higher SL or higher SF in 30m sprint kinematics and performance, but different running strategies emerged from those two warm-ups and a more constant running pattern and performance were found when warm-up focused on higher SF.

The positive effect of warm-up on running performance was previously evidenced by several studies (Gil et al., 2019a; Marinho, Gil, Marques, Barbosa, & Neiva, 2017; Neiva Marques, Barbosa, Izquierdo & Marinho, 2014a; Neiva et al., 2014b). Moreover, some studies found some different running biomechanics during the race (e.g. Gottschall & Palmer, 2000; Mackala, Fostiak & Kowalski, 2015; Morin et al., 2012), but no research investigated the effects of different warm-up running biomechanics and/or technical patterns. In fact, others suggested to exist an acute learning process to each specific exercise that could justify some different biomechanical patterns during trials in other sports (Gil et al., 2019a; Neiva et al., 2014b; Neiva et al., 2017). This acute motor-learning caused by warm-up exercises supported our experimental design; warm-up focused on different technical patterns would result in different running pattern during maximal trial. However, the results obtained were not consistent with this hypothesis and we found no differences on SL and SF during the 30m time-trials. Nevertheless, the different running biomechanics used during warm-up stimulated on a different way the participants so that they used different race strategies.

The WUF resulted in faster initial performances and this might be due to the higher neuromuscular system stimulation required by the exercises performed. Those exercises induced motor neuron excitability that improves the rate of force development and this helped the runners to attain higher SF in the first 15 m lap after the WUF. Probably to compensate for the inability to increase the SF, a higher SL was used in the beginning of the race in the WUL condition. When exercising with higher SF, the runners tend to reduce the portion of the stride the foot is in contact with the ground, rather than the portion taken to swing the limb into position for the next step. On the contrary, longer strides would be cause by applying greater support forces to the ground, increase the runner's vertical velocity on takeoff, thereby increasing both the aerial time and forward distance traveled between steps (Gottschall & Palmer, 2000; Hunter et al., 2004). This would result in different energy and muscle stimulations and thus resulting in different race strategies. The use of higher motor-stimulation as those exercises used in WUF was evidenced to cause increased energy expenditure and higher fatigue in swimming, cycling and running (Gottschall & Palmer, 2000; Neiva et al., 2017). This was proven by the higher HR found after trial in WUF, but not in the [La-] and RPE values.

The warm-up exercises probably increased motor neurons excitability by higher SF used and improved the rate of force development and power production (Ajemian et al., 2010; Neiva et al., 2017; Saez Saez de Villarreal, González-Badillo & Izquierdo, 2007). The runners were able to reach higher velocities in the beginning because of that mechanism. However, the requirements for higher SL during warm-up exercises stimulated the neuromuscular system on a different way that resulted in slower initial meters but faster final meters of the 30m trial. In addition, one does not know if these last faster performances were a result of the lower fatigue caused by the slower running in the beginning of the race. It was also interesting to notice that either performances or running biomechanics seemed to present lower changes between trials in WUF. Moreover, both sprints strategies were similar in both warm-up conditions, suggesting that the stimulation from the warm-up was maintained/prolonged in time.

The manipulation of the running technique during warm-up and the changes in running biomechanics caused different physiological adaptations to the effort. There was an increase in tympanic temperature after warm-up that was different between conditions in pre-trial momentum. The higher values were found in WUL condition, but this was not associated with a greater performance. On the contrary, WUL condition revealed slower initial performances. Previous research suggested that the increase in the temperature is one of the main factors for optimized performance (McGowan et al., 2015; Neiva et al., 2015). In this case, the higher temperatures could be resultant from higher fatigue caused by augmented energy and muscular requirements during the warm-up focused on higher SL. The increased time of muscle contraction per step could also lead to increasing muscle temperature (Campbell, 2008). This augmented muscle temperature takes some time to dissipate and could explain the increased Tymp T during transition period between warm-up and time-trial (Campbell, 2008; Lim, Byrne & Lee, 2008). The higher HR verified after 15min of recovery in WUL compared to WUF highlight for the probability of the higher need for higher recovery times in this warm-up.

Some limitations should be addressed to the current study. The inexistence of significant differences in 30m running performance could be caused by the individual running technique responses to the tested conditions in order to obtain the best result. Perhaps a 3D motion capture system could allow a better comprehension of the biomechanical changes for our results. Also, we should interpret the results knowing that the participants were all males and not sprint specialists. Even knowing the current study limitations, the current findings are still relevant for coaches and researchers to increase the knowledge on warm-up exercises and its effects on running performance.

Conclusions

In conclusion, the results suggested that warm-up focusing in higher SL or higher SF did not result in different 30m sprint performances and running biomechanics. However, both warm-ups induced changes in the strategy used by the runners during both 30m sprints. Faster initial meters were found after WUF whilst faster final meters were found in WUL. Different running strategies emerged from those two warm-ups and more stabilized running pattern and performance values were found when warm-up focused on higher SF was used. The different warm-up protocols seemed to trigger different race strategies to attain similar times, revealing the warm-up's importance in using the appropriate specific exercises for the adjustments intended for the race. Future research should assess different running distances, training levels, technical changes during warm-up and other evaluation methods could be used to complement our measures and to deepen our findings.

Practical applications

The current study took a novel approach to warm-up research by examining the effects of warm-up manipulation in running performance and in running biomechanics. Coaches and researchers should be aware that strategy during short sprints is influenced by warm-up. It seems that WUF may be more important for faster initial performances, whilst WUL may be more significant for the later phases of the race. If the individual race strategy depends on a faster beginning, a warm-up with higher SF should be used, whereas if faster final meters are needed, the warm-up with exercises stimulating greater SL should be used. Moreover, in training, if an athlete needs to work on the first 15m or the last 15m of a 30m sprint to improve his/her performance, they should use WUF or WUL, respectively. In addition, a higher SF during warm-up should be used during warm-up so that biomechanics and running performances can be maintained in repeated sprints. These findings provide new evidences on the relationship between performance and physiological /biomechanical variables during sprint and these findings could provide new insights for researchers, coaches and athletes to improve training efficiency and optimize performances.

Chapter 4. General Discussion

The purpose of the current investigation was to analyze the effects of recent trends of warm-up specific tasks on sprint performance. It was intended to analyze the impact of including ballistic exercises, easy to apply in competition context, and the impact of change running technique during warm-up, in sprint performance. It seemed that, among the various specific trends on warm-up research, post-activation potentiation (PAP) effects caused by short duration maximal efforts, are one of the main focus of recent investigation. Our results showed clear evidences on the positive effect of warm-up in sprints performance. Moreover, it was found that 100m sprint are equally optimized after warm-up with or without PAP exercises, but with different running kinematics according to each condition. However, when evaluating shorter distances (i.e. 30m), the current results suggested that adding ballistic exercises to the typical warm-up did not additionally improve performances. In addition, when assessing the effects of using higher stride length (SL) or higher stride frequency (SF) during warm-up exercises, it was found no different in 30m sprint performances and running kinematics. However, the strategy used by the runners were different during both 30m sprints, suggesting that different warm-up protocols trigger different race strategies to attain similar times, revealing the warm-up's importance in using the appropriate specific exercises for the adjustments intended for the race.

The initial work of this thesis was to briefly review and critically analyze the emerging methods and strategies of warm-up that have been investigated and used before competitive events in recent years (study 1). Most research has shown the positive effects of warm-up on physical performance (Fradkin, Zazryn & Smoliga, 2010), however there are still many areas that need to be understood (Bishop, 2003; Neiva et al., 2015; Wilson et al., 2013; Zois, Bishop, Ball & Aughey, 2011). Further, it seems to exist a difference between the simulated conditions in research and those that occur in real training and competition context. New trends in research have arisen, investigating the use of different warm-ups combined with several different stretching strategies, tasks focused on PAP, and various equipment for passive warm-up that could be used to optimize the usual waiting period between warm-up and competition (Barbosa, Barroso & Andries, 2016; Marinho, Gil, Marques, Barbosa & Neiva, 2017; McGowan, Thompson, Pyne, Raglin & Rattray, 2016; Russel et al., 2015). These recent trends could be useful tools for coaches and athletes trying to maximise performance but can also be used as training strategies to improve velocity and power sets.

Among the specific procedures that we focused on the review, the PAP effects caused by previous exercises has been of great interest in recent years and has been demonstrated to have beneficial effect on performance (Borba, Ferreira-Júnior, Santos, Carmo & Coelho, 2017; Hancock, Sparks & Kullman, 2015). The PAP effects seem to increase force production after a maximum or near maximal muscle stimulation, by neuromuscular changes and improvement of type II muscle fiber activity, thus favouring performance in high-intensity and short-term activities, such as jumping, throwing and sprinting (Docherty & Hodgson, 2007; Kallerud & Gleeson, 2013). It seems that short duration maximal efforts followed by a few minutes of recovery seems to provide beneficial neuromuscular responses and improved performance in high-intensity and short-term efforts (Byrne, Kenny & O'Rourke, 2014; Chiu et al., 2003; Kilduff et al., 2007). However, most of these effects occurred when high-intensity external loads were applied (Chatzopoulos et al., 2007; Rahimi, 2007) and that is very difficult to implement in a real context venue.

Performing exercises aiming to stimulate PAP effects without using external loads are being recognized as a great stimulus during traditional warm-ups for short-term competitive events. The first studies on this revealed that including depth jumping in the warm-up protocol increased both maximal strength (Masamoto, Larsen, Gates & Faigenbaum, 2003) and vertical jump (Hilfiker, Hubner, Lorenz & Marti, 2007; Stieg et al., 2011) and 20m sprint (Byrne et al., 2014). However, there is a lack of investigation on this matter in specific sports performance, such as the Olympic running distances. To the best of our knowledge, until the current research, no studies evaluated the inclusion of ballistic exercises in warm-up before the 100m race and tried to understand the biomechanical responses during the race.

Considering the abovementioned, it seemed relevant to examine the effects of a warm-up including ballistic exercises inducing a PAP, easy to apply on a real competition context, in 100m running performance (study 2). In addition, a second 100m trial was assessed to better understand the warm-up effects during competition and training. The performance, biomechanical variables, physiological variables and psychophysiological variables were evaluated to better understand the effects of warm-up consisting in different strategies. It was found that warm-up, either including or not including ballistic exercises, caused 7.4 and 7.6% faster 100m performances compared to no warm-up (NWU). These results are in accordance with previous scientific evidences that reported optimized sprint performances after a typical warm-up (WU) or a PAP warm-up (e.g. Kilduffet al., 2008; Westet al., 2013) but failed to evidence additional improvement in performances after the use of ballistic exercises, as expected (e.g. Till & Cooke, 2009; Johnson, Baudin, Ley & Collins, 2019). Both warm-ups resulted in higher SF in the second part of the first time-trial compared with no warm-up. Interestingly, SL was higher in the second part of the 100m after PAP compared with WU. Our results corroborated with previous research that suggested that there is a biomechanical adaptation in response to different warm-ups procedures (Neiva et al., 2015, Neiva et al., 2017).The inclusion of ballistic exercises seemed to acutely stimulate the force required for an increased SL and perhaps improving the efficiency of the movement, remaining higher in the beginning of the second sprint. The effects of warm-up on acute motor learning and on sensorimotor responses could lead to different biomechanical movement patterns after different warm-ups (Neiva et al., 2017). It was suggested that there are some specific technical adaptations that occur as response to different warm-up stimulations.

When analyzing the same warm-ups for shorter racing distances (study 3), the benefits of warm-up are highlighted. The warm-up caused faster beginning of the 30m and higher SL in the second part of the time-trial, causing increased blood lactate concentration and higher perceived effort by the participants. However, we failed to evidence additional effects when ballistic exercises are included. Nevertheless, the influence of warm-up in the running technique was highlighted by the changes in the running kinematics and a need for individualization of warm-up procedures. In fact, the experimental studies on 100 and 30 m revealed different adaptations to each condition of warm-up, and the effects were mainly in race strategy (in the case of 30m) or stride kinematics changes (in the case of the 100m). Considering these changes and knowing that some specific technical adaptations that occur as response to different warm-up stimulations, it was our purpose then to the effect of changing the running technique during warm-up on sprint performances, running kinematics, physiological and psychophysiological responses (study 4).

In fact, previous studies suggested existing an acute learning process to each specific exercise that could justify some different biomechanical patterns during trials in other sports (Gil et al., 2019; Neiva et al., 2014; Neiva et al., 2017). This was not confirmed with the results from the study 4. No differences were foundin the 30m sprint performances and in running kinematics after a warm-up focused on exercises with increased SL or SF. Nevertheless, when the warm-up used higher SF, the first 15m of the race were faster, whilst when higher SL was used, the last 15m of the time-trial were faster. Moreover, performances and running kinematics tended to present lower changes between trials when higher SF was used during warm-up. Thus, different running strategies emerged from those two warm-ups and a more stabilized running pattern and performance values were found when warm-up focused on higher SF. Probably, the runners were able to reach higher velocities in the beginning of the race because of increased motor neurons excitability caused by the higher SF used during warm-up (Saez Saez de Villarreal, González-Badillo & Izquierdo, 2007). The faster performances in the final meters could be resultant from the lower fatigue caused by the slower running in the beginning of the time-trial, after the warm-up stimulating higher SL.

Finally, we should not disregard the individual responses for each warm-up, transversal to all experimental procedures. There was an individual response to each condition tested, revealing to the coaches the importance of an individualized approach to warm-up. This was previously highlighted in other studies (e.g. Seitz, de Villarreal & Haff, 2014; Wilson et al., 2013) and it is understood the importance of a proper warm-up structure for optimized performances. However, we should be aware that this sometimes is not possible in training and competition context, and we should further understand the warm-up structure and procedures. The warm-up structure is far from being well known and investigation should be continued. These and future evidences about warm-up will impact on the ability to provide efficient information for professionals, researchers and athlete and to maximize research, training programs, and specific tasks that require a previous warm-up.

Some main limitations of this thesis should be addressed:

- One should acknowledge possible unknown variation in day-to-day performance, despite the counterbalanced distribution of the participants;
- These studies were performed in short distance running and different Olympic race distances would elicit different adaptations;
- The PAP should have been individually assessed previously to the study, to design a more appropriated rest after the ballistic exercises;
- Several physiological measures should have been included to better understand and explain the results (e.g. muscle temperature and core temperature);
- Larger samples and higher skilled sprinters could allow more consistent results.

Chapter 5. Overall Conclusions

The main findings of this work emphasize the importance of the warm-up and its design for short running distances. Data also showed the relevance of the individualization of warm-up for optimized performances, highlighting the need for tailored and customized warm-up designs and specifically when using post-activation potentiation (PAP) strategies during warm-up and changes in running technical pattern. Regarding the specific purposes, the conclusions of the present thesis were:

i. New trends in research have emerged, and it can be suggested that short duration stretches can be used, followed by another specific muscle activation according to subsequent main activity; dynamic stretching seemed to cause more improvement than static stretching, and both depended on the duration and intensity; short-duration maximal efforts and specific to the following activity, followed by few minutes of recovery, provide beneficial neuromuscular responses and improved performance in high-intensity and short-term efforts; passive heating during the transition phase between warm-up and main exercise lead to optimization of subsequent performance;

ii. The results highlight the positive effects of warm-up for 30m and 100m sprinting performance;

iii. The 100m race is equally optimized after warm-up with or without PAP, but with different running kinematics. The inclusion of ballistic exercises can increase stride length (SL) in the final meters of the 100m race;

iv. The 30m running was positively influenced by typical warm-up procedures, by a faster beginning and increased SL in the second half of the time-trial, compared to no warm-up;

v. The inclusion of ballistic exercises in warm-up did not reveal differences in 30m sprint. On contrary, the second 30m sprint revealed slower performances compared with warm-up without those ballistic exercises;

vi. It was shown the need for tailored and customized warm-up designs and specifically PAP strategies during warm-up;

vii. A warm-up focusing in higher SL or higher stride frequency (SF) did not result in different 30m sprint performances and running kinematics. However, different running strategies occurred with faster initial meters after warm-ups stimulating SF and faster final meters after warm-up stimulating SL.

Chapter 6. Suggestions for future investigations

There is a lot to know about warm-up in running and a few indications for possible future investigations are listed below:

- To replicate these studies but with different running distances events, to understand the warm-up effects on different races;
- To develop different protocols to induce post-activation potentiation (PAP), easy to apply in a competition venue;
- To improve passive and active strategies after finishing warm-up so that athletes can benefit from all the positive effects of warm-up;
- Future research should investigate different PAP strategies (e.g. combining different jumps or short-term sprints) and different recovery times between the warm-up and the race;
- Other evaluation methods could be used to complement our measures and to deepen our findings, such as body temperature and other biomechanical variables (e.g. contact time and horizontal forces production);
- The response to warm-up should be deepened regarding not only physiological measures, but to understand biomechanical and technical responses to each condition assessed;
- More detailed information should be provided with practical applications is needed for coaches and researchers, and the understanding of warm-up effects on performance but also in fatigue should be developed.

Chapter 7. References

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Appendix III

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Appendix I

Complementing Warm-up with Stretching Routines: Effects in Sprint Performance

Abstract

The present study aimed to examine the effects of using static or dynamic stretching added to the common warm-up routine for short sprint distances and to repeated sprint performance. In 3 different sessions, 16 college-age men (n = 10) and women (n = 6) performed one of 3 warm-ups followed by a 2 × 60 m dash sprint time trial (5 min of rest) in a counterbalanced design. The control warm-up consisted of 10min of light-intensity running, and the 2 experimental warm-ups included a static stretching (SS) or dynamic stretching (DS) routine (5 exercises) in the control warm-up. Performance (time) and physiological variables (tympanic temperature, heart rate) were monitored. In the first 60m time trial, there were no differences between the 3 warm-ups tested ($F = 0.21$, $p = 0.73$; $\eta_p^2 = 0.01$), as opposed to that observed in the second ($F = 7.04$, $p< 0.01$; $\eta_p^2 = 0.32$). The participants were 1.7% faster after the SS warm-up compared with the control warm-up. The sum of the time performed in the 2 sprints emphasizes these results, with better performances after the SS warm-up than the control (1 %) or DS warm-up (0.7 %). These results suggest that including a set of SS or DS exercises may enhance sprinting performance. The better performance in the second trial after the warm-up including SS suggests that this type of stretching may positively influence repeated sprint performance (< 10s sprint).

Key-Words: Pre-exercise, Repeated-sprint, Evaluation, Velocity, Heart rate, Tympanic temperature

Introduction

Stretching during the warm-up is a key routine in training and physical fitness programmes (Magnusson & Renstrom, 2006; Neiva, Marques, Barbosa, Izquierdo & Marinho, 2014). Practitioners claim that stretching can enhance performance and reduce the incidence of musculoskeletal injury and the onset of the delayed muscle sourness (Magnusson & Renstrom, 2006; Witvrouw, Mahieu, Danneels & McNair, 2004). However, evidence has challenged these arguments (Behm & Chaouachi, 2011; Kay & Blazevich, 2012).

Some researchers noted that static stretching routines caused impairments in strength, power, maximal strength development, vertical jump and short sprinting performances (Kay & Blazevich, 2012; Ribeiro & Del Vecchio, 2011). The results seems particular harmful when stretching to the point of discomfort, considered to be maximal stretching intensity (Behm & Chaouachi, 2011; Young & Behm, 2003). Some evidence in the literature suggests that submaximal stretching intensities (for example, 90 % of maximal range of motion), might not produce such impairments (Young, Elias & Power, 2006). However, there is more agreement that dynamic stretching (DS) seemed to produce better performance in subsequent physical bouts, even in short-duration efforts (Behm & Chaouachi, 2011; Ribeiro & Del Vecchio, 2011).

Nevertheless, several methodological limitations could be noted. Most studies implemented static protocols ranging between 90s to 30min duration for each muscle group, which is clearly different from what usually occurs in real settings (Beckett, Schneiker, Wallman, Dawson & Guelfi, 2009; Behm & Chaouachi, 2011; Kay & Blazevich, 2012). In field settings, subjects stretch each muscle group from 10–30s, with 2 or 3 repetitions, and mostly to the point of discomfort. Additionally, those studies tended to analyse the effect of stretching in an isolated form and not as a complementary routine to a warm-up session that aimed to increase subject preparedness for exercitation (McGowan, Pyne, Thompson & Rattray, 2015). Moreover, researchers focused mostly on the evaluation of a single maximal effort and little is known about the effect of stretching on repeated maximal efforts (McGowan, Pyne, Thompson & Rattray, 2015).

The controversy still exists and the effect of static or dynamic stretching in maximal efforts or in repeated maximal efforts is unknown. Moreover, it seems appropriate that in activities requiring a high range of motion, the athletes should select drills preparing themselves to reach the optimal range of motion and therefore enhance performance. Accurate studies are lacking on whether adding stretching routines to the warm-up could enhance performance without any impairment (McHugh & Cosgrave, 2010). Therefore, the purpose of this study was to verify the effects of added stretching (static vs. dynamic) exercises in a warm-up routine on sprinting performance and physiological response. In addition, we intended to understand the effect of both warm-ups in a second time-trial repetition. It was hypothesised that a warm-up including DS exercitation would improve sprint performance, also leading to an increased tympanic temperature (Tymp T) and lower heart rate (HR) responses to exercise.

Material and methods

Subjects

A convenience sample of 16 college students (10 males and 6 females; 22.00 ± 1.55 years old; 1.72 ± 0.08 m of height; 66.86 ± 12.20kg of body mass) took part in this study. All participants were physically active and competed at the university level for the last 2.63 ± 1.41 years. Table 1 presents the subjects' characteristics. After approval by the university ethics committee to ensure compliance with the Helsinki declaration, participants were informed about the study procedures and written informed consent was obtained. Additionally, this study was performed in accordance with the ethical standards proposed by Harris and Atkinson (2015).

Table 1. Characterization of the male and female participants.

	Age (years)	Height (m)	Body mass (Kg)	Body mass index (Kg/m^2)	Training experience (years)
Males (n = 10)	22.10 ± 1.52	1.76 ± 0.06	74.23 ± 8.57	23.92 ± 2.27	2.50 ± 1.72
Females (n = 6)	21.83 ± 1.72	1.65 ± 0.05	54.57 ± 4.92	20.13 ± 0.93	2.83 ± 0.75
Total (n = 16)	22-00 ± 1.55	1.72 ± 0.08	66.86 ± 12.20	22.50 ± 2.64	2.63 ± 1.41

Testing procedure

The experiments were performed over a 3-week period on an official running track at the same time of the day and with similar weather conditions. Air temperature remained between 19 °C and 21 °C (19.80 ± 0.92 °C) and wind < 2m/s.

The study followed a randomized crossover design. 3 warm-up procedures were tested: (i) control warm-up (no stretching routine included), (ii) static stretching (SS) warm-up, and (iii) dynamic stretching (DS) warm-up. Each warm-up condition was tested with 48 h between them in randomized order. The subjects were familiarised with the warm-up procedures one week before the first evaluation and they were reminded to maintain the same routines during the 48h prior to testing. After finishing the warm-up, each subject remained seated for 5min and then completed 2 time trials of 60m running (5min rest between bouts).

The stretching activities were those that the athletes normally used in their daily warm-up routines. The control warm-up consisted of 10 min of continuous running at moderate intensity (50 to 70% of predicted maximal HR), as suggested in the literature (Yaicharoen, Wallman, Morton & Bishop, 2012). The SS consisted of the same running activity as the control warm-up followed by a SS sequence of 5 exercises, completed in 8–10 min. All stretches were repeated for 3 sets of 30s (15s interval) and held at the point of mild discomfort. The static exercises included: i) hamstring stretch (grab the knee and pull it straight up, towards the chest); ii) standing quadriceps stretch (grab the foot and pull it back to gluteus); iii) standing hamstring stretch (one leg on an elevated support, bend from the lower back and reach forward, keeping the legs straight); iv) seated hamstring stretch (with the knee of one leg bent and the other leg extended, bend the waist toward the extended leg); v) lying quadriceps stretch (lie on side and pull heel toward buttocks until a stretch is felt in front of the thigh). The DS warm-up was similar but replaced SS warm-up with a DS sequence of 5 exercises, completed in 8 to 10min. The DS were performed over a 20 m course and the exercises used were the same as those of Turki et al. (2012).

Official start commands were used and time trials started from the official starting block. The 60m trial was chosen because it is the shortest IAAF event. In addition, research with regard to the influence of warm-up at this particular distance and in repeated 60m sprints is scarce (McGowan et al., 2015). Time trial performances were recorded by photocells (Polifemo Radio, Microgate, Bolzano-Bozen, Italy) at the 0, 20, 40, and 60m mark and at 1.17m above the floor.

After arriving at the track, the athletes remained seated for 5min, with the legs uncrossed, to assess baseline measurements. Tympanic temperature measurements were assessed before the warm-up (baseline measures), immediately before each one of the two 60m bouts (1min), and 5min into recovery. This is a good indicator of brain temperature, which controls body temperature, and each Tymp T was taken 3 times, and the maximal value was recorded (Braun Thermoscan IRT 4520, Germany). The thermometers had a measuring accuracy of 0.2°C for temperatures between 32.0 and 42.0°C. The HR was also assessed at baseline, immediately before each trial (1 min) and 5 min after the second 60m bout (Vantage NV; Polar, Lempele, Finland). During that time, the participants remained seated. Each physiological measurement was performed 3 times, for each evaluation, and the highest value was recorded (ICC> 0.97).

Statistical analysis

The normality of all distributions was verified by the Shapiro–Wilk test and parametric statistical analysis was used. Standard statistical procedures were selected for the calculation of means, standard deviations (SD) and 95% confidence intervals. The effect of the warm-up procedures was analysed by an ANOVA for repeated measures, with sphericity checked using Mauchly's test. When the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse-Geisser procedure. Posthoc paired t-tests were run to further investigate the effect of each condition. Effect size (ES) was calculated to estimate variance between conditions (partial eta squared: η_p^2) and Cohen's dz (ES) for within subject comparisons (Lakens, 2013). Interpretation of ES was based on Cohen (1992) and 0.2 was deemed small, 0.5 medium, and 0.8 large for ES values. For η_p^2, cut-off values were interpreted as 0.01 for small, 0.09 for moderate and 0.25 for large. The level of statistical significance was set at $p \leq 0.05$.

Results

Baseline HR and Tymp T showed no variations between the days of testing (Tymp T: $F_{(2,\ 30)} = 0.63$, $p = 0.54$; $\eta_p^2 = 0.04$; HR: $F_{(2,\ 30)} = 0.41$, $p = 0.67$; $\eta_p^2 = 0.03$), ensuring the same conditions on different days.

Table 2 presents the values recorded after each warm-up condition in the time trials and partials in detail. In addition, Figure 1 presents the changes verified between conditions. There were no variations in the first time trial between warm-ups ($F_{(1.37,20.57)} = 0.21$, $p = 0.73$; $\eta_p^2 = 0.01$). However, large variations were noted in the second 60m sprint ($F_{(2,\ 30)} = 7.04$, $p = 0.003$; $\eta_p^2 = 0.32$). The participants were 1.7 % faster (95 % CI: 1.0 to 2.4 %) after SS warm-up compared to control condition. Moderated positive effects were found after DS warm-up condition when compared to control, with 0.8 % (95% CI: −0.2 to 1.8%) faster performances. Between the 2 warm-ups that included stretching routines, the SS produced better performances (0.9%; 95% CI: − 0.1 to 1.8%).

The values obtained from the sum of the 2 time trials highlighted the benefit of SS warm-up, with lower times than either the control warmup (1.0%; 95% CI: 0.2 to 1.9%) or DS warm-up (0.6%; 95% CI: −0.3 to 1.5%).

As far as the physiological variables are concerned, the heart rate was different between conditions before the first sprint ($F_{(2,\ 28)} = 5.10$, $p = 0.01$; $\eta_p^2 = 0.27$) and the second sprint ($F_{(1.28,\ 17.98)} = 4.017$, $p = 0.05$; $\eta_p^2 = 0.22$). Higher values were found in the control condition compared to SS warm-up (first sprint: $p = 0.01$, ES = 0.82; second sprint: $p = 0.02$, ES = 0.70, or DS warm-up (first sprint: $p = 0.04$, ES = 0.67; second sprint: $p = 0.05$, ES = 0.55). No differences were found in Tymp T before the first ($F_{(2,\ 30)} = 0.86$, $p = 0.43$; $\eta_p^2 = 0.05$) and the second trial ($F_{(2,\ 30)} = 2.59$, $p = 0.09$; $\eta_p^2 = 0.15$). Significance appeared only after the 5 min of recovery ($F_{(2,\ 30)} = 3.32$, $p = 0.05$; $\eta_p^2 = 0.18$), with increased values of the control condition compared to SS warm-up ($p = 0.02$, ES = 0.64) or DS warm-up ($p = 0.04$, ES = 0.55). Figure 2 illustrates these results with respect to the physiological variables.

Table 2. Time performed in the 60m time trials after each warm-up condition (mean±SD). Differences, p-values and effect sizes (ES) are also presented (n = 16).

		Control	Static Stretching (SS)	Dynamic Stretching (DS)	Control vs. SS			Control vs. DS			SS vs. DS		
					Difference (mean±95% CI)	**p-value**	**ES**	**Difference (mean±95% CI)**	**p-value**	**ES**	**Difference (mean±95% CI)**	**p-value**	**ES**
Time trial 1(s)	**0-20m**	3.16 ± 0.31	3.17 ± 0.30	3.16 ± 0.30	0.01 ± 0.05	0.59	0.14	0.00 ± 0.03	0.98	0.01	-0.01 ± 0.04	0.52	0.17
	20-40m	2.70 ± 0.37	2.69 ± 0.36	2.70 ± 0.34	-0.01 ± 0.02	0.48	0.18	0.00 ± 0.02	0.92	0.02	0.01 ± 0.03	0.58	0.14
	40-60m	2.79 ± 0.42	2.76 ± 0.42	2.79 ± 0.39	-0.03 ± 0.05	0.26	0.29	0.00 ± 0.03	0.81	0.06	0.03 ± 0.05	0.30	0.27
	0-60m	8.66 ± 1.09	8.63 ± 1.07	8.65 ± 1.03	-0.03 ± 0.05	0.63	0.12	-0.01 ± 0.06	0.87	0.04	0.03 ± 0.10	0.54	0.12
Time trial 2(s)	**0-20m ***	3.15 ± 0.33	3.11 ± 0.30	3.13 ± 0.30	-0.04 ± 0.03	0.02	0.64	-0.01 ± 0.03	0.41	0.21	0.03 ± 0.04	0.20	0.34
	20-40m **	2.69 ± 0.37	2.64 ± 0.33	2.67 ± 0.35	-0.05 ± 0.03	0.005	0.83	-0.02 ± 0.03	0.35	0.24	0.04 ± 0.03	0.03	0.61
	40-60m ***	2.79 ± 0.43	2.72 ± 0.41	2.74 ± 0.40	-0.06 ± 0.03	0.001	1.04	-0.05 ± 0.04	0.04	0.58	0.02 ± 0.04	0.48	0.18
	0-60m*	8.62 ± 1.12	8.47 ± 1.03	8.51 ± 1.03	-0.16 ± 0.07	0.001	1.07	-0.08 ± 0.09	0.11	0.43	0.08 ± 0.08	0.08	0.46
Sum TT1 + TT2 (s) *		17.28 ± 2.20	17.09 ± 2.10	17.20 ± 2.06	-0.19 ± 0.16	0.04	0.58	-0.08 ± 0.12	0.20	0.33	0.10 ± 0.16	0.23	0.31

* Differences between control and SS (p < 0.05)

** Differences between control and SS, and between SS and DS (p < 0.05)

* Differences between control and SS, and between control and DS (p < 0.05)

CI: confidence interval; ES: Effect Size; TT1: Time trial 1; TT2: Time trial 2; SS: Static stretching; DS: Dynamin stretching

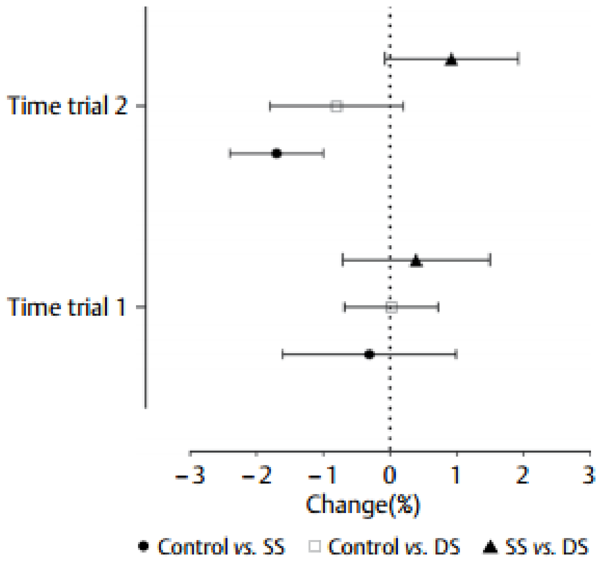

Figure 1. Changes verified between conditions

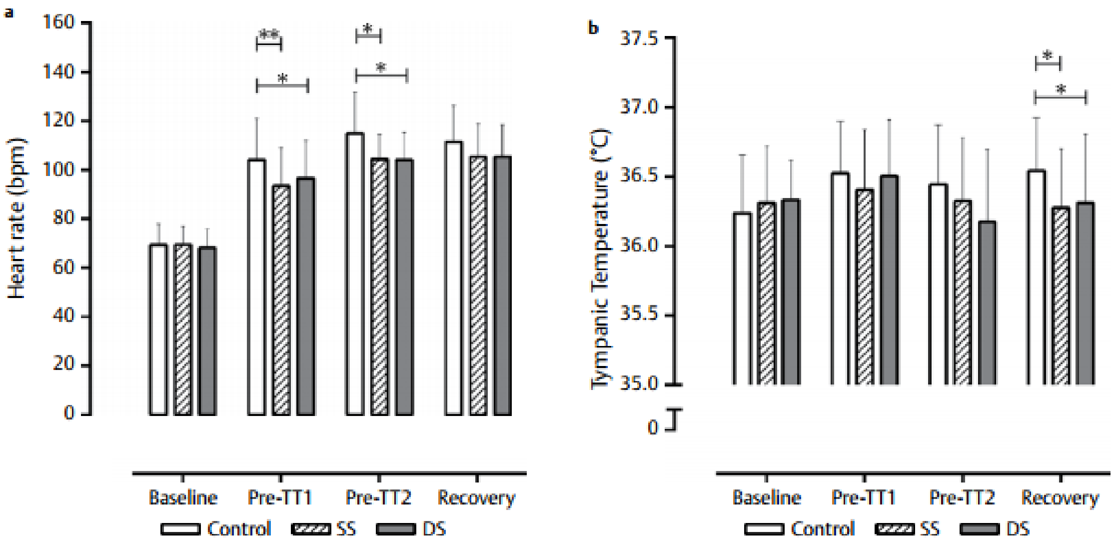

Figure 2. Physiological variables responses to control, static stretching (SS) and dynamic stretching (DS) warm-ups at baseline, before the first time-trial (Pre-TT 1), before the second time-trial (Pre-TT 2) and after 5min recovery: **a**heart rate and **b**tympanic temperature. * indicates $p < 0.05$ and ** indicates $p<0.01$. Data presented as mean ± SD (n = 16).

Discussion

The main aim of this study was to compare the effects of stretching during a warm-up routine before a short-distance sprint (60m). In addition, it was intended to verify the influence of different warm-ups in repeated-sprint performance. There were no differences between conditions in the first 60m sprint, suggesting that including SS or DS after a light-intensity continuous run does not affect sprinting performance. However, a second repetition of 60m improved when stretching was included in the warm-up routine, notably SS.

The different warm-ups evaluated did not show differences in the first time-trial performance. These results are contrary to other studies reporting the benefits of dynamic instead of SS (Behm & Chaouachi, 2011; Gelen, 2010; Needham, Morse & Degens, 2009). The DS could improve the performance in the short sprint and all-out bouts because of the similarity of motor pattern used, the increased body temperature obtained by the movement, the proprioceptive facilitation and better pre-activation for the subsequent task (Gelen, 2010; Needham et al., 2009). On the other hand, SS is expected to affect musculoskeletal stiffness, leading to an impairment of the potential elastic energy stored by the stretch-shortening cycle (Winchester, Nelson, Landin, Young & Schexnayder, 2008), and/or to more challenging neuromuscular stimulation because of the diminished activity by the muscle proprioceptors (Kistler, Walsh, Horn & Cox, 2010). Nevertheless, there were reports that muscle-tendon properties "in vivo" remained unchanged after the SS, which is not in line with the evidence reported early on (Morse, Degens, Seynnes, Maganaris & Jones, 2008). Moreover, Kay and Blazevich (2012) mentioned that most studies on this topic did not observe impaired performances in strength, power, or velocity when stretching for less than 45s. Negative effects arose only when static stretching was performed for more than 60s. The results of the present study partially support this report.

In the SS warm-up, participants were better in each 20m split and hence in the 60m time trial. The role of the first maximal repetition seemed to be a key factor for these results. Performing dynamic movements and activities after SS could reduce the possible negative effect on performance, reversing any undesirable muscular effect or associated neural effects (Little & Williams, 2006; Rosenbaum & Hennig, 1995). Furthermore, recent evidence showed that only 10min should be needed to restore the maximal values of isometric strength after 5min of static stretching (Mizuno, Matsumoto & Umemura, 2014). Thus, in the present study, the second bout was held beyond this 10min interval. Subjects could even have benefited from gains in muscular range of motion that might remain elevated for 30min after SS (Mizuno, Matsumoto & Umemura, 2013). It is plausible that one can propose a possible potentiation effect caused by the first maximal repetition. This caused an improvement in all conditions tested. This maximal activity could result in increased neuromotor excitability, which leads to a considerable increase in the rate of force development and power production (Saez Saez De Villarreal, González-Badillo & Izquierdo, 2007). Therefore, including a short-duration task at maximal intensity or even a racepace task before the race or the training main set could maximize performance.

The acute response to warm-up showed that all 3 warm-ups elevated body temperature and HR, as expected (McGowan et al., 2015; Neiva et al., 2016; Neiva et al., 2017). Most of the effects of warm-up are related to an increase in body temperature, oxygen uptake and HR

(McGowan et al., 2015). Those gains theoretically also support a positive effect on sprint performance. For instance, it is known that an increase in muscle temperature can lead to better sprint performance by increasing muscle glycogen availability in short-term efforts (Gray, De Vito, Nimmo, Farina & Ferguson, 2006). The temperature responses together with HR would allow us to interpret the performance results obtained, caused by the different warm-up conditions. In fact, HR is easy to monitor in the field context and shows a very stable pattern that allows coaches and athletes to verify and adjust the exercise intensity. Because the intensity of trials was maximal and the sprints were short in the present study, the acute responses were expected to be minimal. However, the HR adaptation to each warm-up condition during all procedures allowed us to verify different energy expenditures (Jeukendrup & Van Diemen, 1998) and to explain possible causes for different performances.

Exercise intensity is usually related to the amount of energy expended to perform a certain activity (Jeukendrup & Van Diemen, 1998). In non-laboratory settings, HR can be used to compare energy expenditures between exercises (Achten & Jeukendrup, 2003). We noted that the increase in HR was higher in the control warm-up, possibly resulting from the continuous activity that was completed without the “interval” associated with the stretching exercises. In fact, one possible explanation for the better performance obtained in the sum of the two 60m sprints in SS warm-up could be related to the higher energetic expenditure in the other 2 warm-ups. The 5min interval between warm-ups and the beginning of the time trials could not allow full replenishment of ATP-PCr reserves, essential to an effort of less than 10 s duration (Gastin, 2001). Contrary to the control and DS warm-up, which comprised physical effort during all warm-up protocols, the SS warm-up comprised lighter activities, very close to a resting situation. Therefore, in this warm-up condition, the energy expenditure could be almost null and could allow starting the recovery phase after the first sprint earlier than the others. This temporal gain allowed the full recovery of the energy storage and of the neuromuscular system (McGowan et al., 2015).

We could also suggest that the post-activation potentiation (PAP) caused by the first sprint allowed greater improvement in the second sprint after a warm-up with SS routines. Coaches should be aware of this evidence, not only for when athletes are competing more than once in the same competition session or during training sessions where maximal repetitions appear essential to increase preparedness, but also in intermittent sports (e.g., team sports) performance.

Conclusions

The current results suggest that including a stretching exercise routine, static or dynamic, during warm-up could be a reliable option when preparing for short-distance repeated-running performances. It was verified that the second 60m repetition was faster than the first when SS was used as a complement to a simple running warm-up. This fact seems to suggest that the warm-up, when complemented with stretching exercises, positively influences repeated sprint ability.

Appendix II

The effect of warm-up on sprinting kinematics

Abstract

The purpose of this study was to verify the effects of warm-up on kinematic variables during short distance repeated sprints. Twenty-two college students randomly performed 2 x 30-m running time-trials after warm-up or with no warm-up, in different days. Performance (time-trial) and biomechanical (step length (SL) and step frequency (SF)) were assessed during both repeated trials. Performance was 0.5% faster after warm-up in the first 30-m time-trial ($p = 0.03$, $d = 0.44$), but without differences on SL and SF. The second sprint was not different between conditions, but it was better than the first sprint in the no warm-up condition. This condition also led to higher changes between the first and second sprint. Thus, the warm-up is suggested to improve maximal running performances and maintaining kinematics more similar throughout the sprints.

Key-Words: pre-exercitation, running, length, frequency

Introduction

Warm-up is usually assumed to be the first part of physical activity and it is accepted to be fundamental to enhance the performance and prevent injuries. Despite the limited evidences demonstrating its efficacy, the scientific community supports the use of warm-up as a preparing activity (McGowan, Pyne, Thompson & Rattray, 2015). It has been suggested that the rise in muscle temperature caused by the priming exercises results in multiple physiological and metabolic changes, and is the major contributing factor to positively influence performance. Simultaneously, some recent research found different biomechanical responses to the use of warm-up in swimmers (Neiva et al., 2014) and an effect of warm-up on acute motor learning and on sensorimotor responses that led to different biomechanical movement patterns after different swimming warm-ups (Neiva et al., 2016). Specifically in running, most of the studies focused on performance and physiological variables without the full understanding of the effects of warm-up. In fact, there is a scarcity of knowledge about the effect of warm-up on the biomechanical variables of running and that could be critical to training and performance. In recent years, warm-up has emerged as one of the main concerns to coaches, athletes and researches, evidenced by the increase in publications about this subject. This novel focus analysis of the biomechanical effects could provide useful information for performance optimization. Thus, the purpose of this study was to analyze the effect of warm-up on the kinematics of short running sprinting performance.

Methods

Twenty-two male college students volunteered to participate in this study (mean ± SD: 19.32 ± 1.43 years of age; 1.76 ± 0.67 m height; 68.48 ± 9.91 kg body mass). After local ethics board approval, ensuring compliance with the Declaration of Helsinki, the participants were informed about the study procedures, and a written informed consent was obtained from the subjects. All the procedures took place at the same time of the day (14h- 18h PM) at a multi-sport indoor facility (more than 50m long). The study followed a repeated measures design. Each participant completed 2 sessions of 2 maximal 30-m sprints, in randomized order, separated by 48h. They were reminded to maintain the same diet and activity routines during all the procedures. After arriving facilities, each participant remained seated for 5min to rest and concentrate on the procedures. Then, they were assigned to each protocol (standard warm-up or without warm-up). The standard warm-up was designed based on research (McGowan et al., 2015) and with the help of an experienced coach, and comprised 5min of easy run, 5min of drills and then 2 short distances of progressive running speed. Following the warm-up, participants rested for 5min (seated) and then 2 time-trials of 30-m running were performed with 5min of interval between. The sprint times were recorded using Brower equipment (Wireless Sprint System, USA). All the procedures were recorded by two video cameras (Casio Exilim Ex-F1, f=30Hz) placed perpendicular to the running track. For each run of each subject, the average step length (SL) and step frequency (SF) over the whole 30-m distance were analysed. The total number of steps taken in the race by each of the subjects was counted using the Kinovea® software (version 0.8.15) and SL and SF were derived from that, knowing time and distance performed. Standard statistical procedures were selected for the calculation of means, standard deviations (SD) and 90% confidence interval. The normality of all distributions was verified using Shapiro-Wilks tests. To compare data between two trials, Student's paired t-tests (parametric) was used and the alpha level was set at $p < 0.05$. Cohen's d effect size (ES) was determined and 0.2 was considered small, 0.5 medium, and 0.8 large (Cohen, 1988).

Results

Performance was significantly better in the first sprint after warm-up than without warm-up, while no differences were found in the second 30-m time-trial (Table 1). In Table 1 are shown that, in both sessions, there were no differences between the biomechanical variables between using and not using a previous warm-up.

Table 1. Mean ± SD of performance and biomechanical variables in 30-m run. Significance (p-value) and effect size (ES) are presented (n=22).

	Without Warm-up	With Warm-up	Mean Difference (%)	p-value	ES
1st 30-m (s)	4.67 ± 0.20	4.58 ± 0.20	-0.5	0.03	0.44
2nd 30-m (s)	4.60 ± 0.23	4.56 ± 0.22	-1.0	0.27	0.17
1st SF (Hz)	4.27 ± 0.25	4.31 ± 0.25	1.7	0.54	0.16
2nd SF (Hz)	4.29 ± 0.31	4.30 ± 0.18	2.6	0.86	0.04
1st SL (m)	1.51 ± 0.06	1.52 ± 0.07	2.2	0.38	0.15
2nd SL (m)	1.53 ± 0.08	1.54 ± 0.07	1.5	0.65	0.13

There were differences in time between the first and the second 30-m sprint when no warmup was performed before ($p = 0.008$, $d = 0.32$). No significant differences were found between the first and the second sprint in the other variables. However, without warm-up the changes were always higher than with warm-up. These changes between first and second time-trial are presented in Figure 1. Note that the 30-m sprint were calculated based on time, which means that the higher the improvement, the lower the values of change.

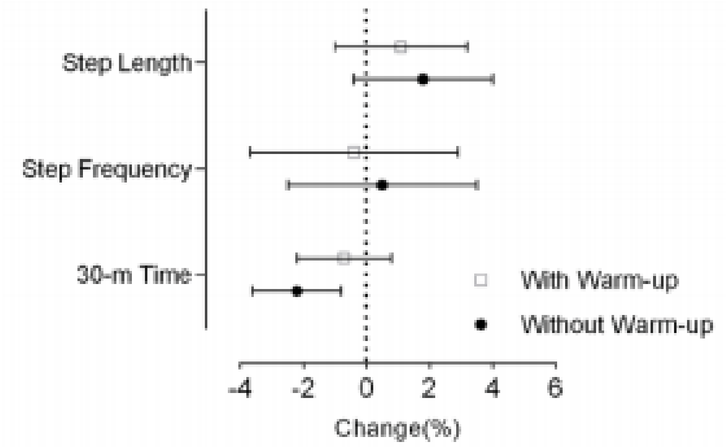

Figure 1. Mean changes (± 90% CI) between the first and second 30-m sprint with and without warm-up.

Discussion

The aim of this study was to verify the effects of a standard warm-up protocol on the 30-m repeated sprint performance and to analyse the effects on the running SL and SF variables. The main finding was that performance was improved after warm-up comparing to no warm-up condition. However, this difference was not reflected on the SL and SF analysed. Still, we could verify that there was a tendency to maintain the values from the first to the second sprint in all variables. This could indicate a maintenance of the technical aspects of the run after warm-up, revealing the importance of a proper warm-up before sprints and repeated sprints performances. In competition or training venue, the runners are used to complete any kind of active warmup to increase their preparedness to the subsequent activity. Despite this usual practice, there is a lot to know about the real effects of warm-up in the different components of the performance, such as physiological and biomechanical. To the best of our knowledge, only one research focused on the biomechanical changes of running caused by warm-up, analysing shoulder lean, hip flexion and forward lead with improved positions but without improved 36.6 m performances (Smith et al., 2014). On the contrary, our results showed better sprint performances after warming-up but without kinematic changes. In fact, the positive effect of warm-up in sprint was already widely evidenced in recent years (McGowan et al., 2015), and our results agreed. However, we may be expecting that SL and SF could differently respond to the different level of preparedness as literature suggested in other sports (Neiva et al., 2014). Perhaps, this similarity could be explained the low level of the subjects, once elite runners perform more efficiently than less experienced runners (Padulo et al., 2012). Even so, the results revealed a propensity for a higher SF and SL in the warmup condition, in the first sprint, where the differences in performance were significant. Runners adapt their optimum SL and SF to get the most efficient running for the speed performed and according to their own characteristics (Salo, Bezodis, Batterham & Kerwin, 2011). The inexistence of significant differences could be caused by the individual kinematic responses to the conditions tested trying to obtain the best result. Perhaps a 3D motion capture system could allow a better knowledge of the biomechanical changes for our results. Knowing this and based on these results, we can suggest further research on the changes in technical pattern of runners according to the warm-up previous performed. The second sprint led to no different performances between conditions. As expected, the first sprint may have worked not only as a warm-up for the unheated condition, but also as an enhancer of performance, increasing the neuromotor excitability that can optimize performance in a second sprint (Spencer, Bishop, Dawson & Goodman, 2005). Actually, the minor changes from the first to the second sprint were verified when warm-up was done. We could suggest that fewer changes in technique occur in this condition. This could mean a better preparedness for maximal running and lower influence of fatigue in the second sprint that could cause changes in running kinematics.

Conclusion

This study revealed the importance of warm-up to maximize short distance running performance. In fact, the use of a standard warm-up led to better performances in the first one of the two sprints. However, it seems that a standard warm-up did not result in more than small effects in SL and SF compared to the no use of warm-up. Even so, the results tend to change more from the first to the second sprint when there was no warm-up. Our findings could be useful for coaches, as there were clear evidences that warm-up is beneficial to performance and it was showed that the running performance and running technique seems to be more stable when a warm-up is accomplished before maximal repeated sprints. Coaches should focus on the use of a proper warm-up that can maximize performance and sustain technical aspects, perhaps delaying fatigue. This is especially relevant during training sets where several repetitions of maximal efforts are performed. To the best of our knowledge, this was the first investigation trying to understand the changes in SL and SF in running, specifically in short sprints, and further research should developed to better understand the most appropriated warm-up to optimize running performance.

Appendix III

Correlations between biomechanical variables and 30m sprint running

Abstract

Introduction: Sprinting contributes to successful performance in the wide range of sporting activities. It is known that sprinting speed is defined by the stride frequency (SF) and the stride length (SL) (Čoh, Tomažin & Rausavljević, 2007). According to Bezodias et al. (2008) the SF was a more important contributor to the velocity increase in sprint performance, however for Mackala (2007) the SL was a more significant variable. The aim of this study is to determine if different types of warm-up can interfere with the SF and SL variability. **Methods:** 22 young men participated in this study (age: 19.32 ± 1.43 years; height: 176 ± 67cm; weight: 68.48 ± 9.91kg). The study followed a randomized protocol and the subjects were submitted to three warm-up protocols: no warm-up (NWU), typical warm-up (WU) and warm-up with post-activation potentiation (PAP). **Results:** The results reveal strong correlations between the 30m sprint time and the SF and SL. **Discussion:** Regardless of the type of warm-up, we can observe that the SF and SL are relevant factors that contribute to sprint time performance. The results corroborated with other studies indicating that maximum speed results from an optimal ratio between SF and SL. **Conclusion:** The SF and SL were shown to be two important factors in the sprint time of 30m. We suggest that future studies include exercises on warm-up that stimulate the SF and SL, in order to verify which of the variables has the greatest impact on sprint performance.

Key-Words: stride frequency, stride length, sprint time.

Table 1. Correlations between 30m sprint performance and biomechanical variables

Sprint time (s)	Stride Frequency (Hz)	Stride Length (m)
No Warm-up (NWU)	**-0,699****	**-0,529***
Typical Warm-up (WU)	**-0,598****	-0,352
Warm-up with PAP (PAP)	**-0,702****	**-0,551****

*Significance: *p<0,05; **p<0.01*

Appendix IV

External heating garments used post-warm-up and effects in sports performance

Abstract

Introduction: There are several studies that have reported significant losses in body temperature and athletic performance after the transition between warm-up period and sport competition. The passive temperature maintenance is one method used to attenuate the reduction in body temperature, yet literature remains unclear on this issue. **Objectives:** This study aimed to present some data on the benefits of using thermal garments in the transition period between warming-up/heating and sports events. **Methods:** This work was based on articles indexed in several databases as ISI Web of Knowledge, PubMed and ScienceDirect. For further analysis the following keywords were included separately and/or combined: post warm-up, passive heating, external heating, garments of heating. **Expected Results:** The passive heating involves the use of specific methods (i.e. thermal garments, survival jackets and heating pads) to attenuate heat loss. These are easily to administrate in order to maintain specific muscles temperature. An interval of 30 minutes leads to a decrease in muscle temperature (Tm) and core temperature (Tc). In turn, passive temperature maintenance during the interval reduces the decline in Tc, leading to an improvement in peak power as well as repeated sprint capacity. A 1°C reduction in Tm leads to a 3% reduction in muscle power of the legs and the increase of 1ºC in Tm can improve 2-5% of the subsequent performance. In conclusion, the use of thermal garments during the transition phase between warming-up and the sports events can be of great importance in maintaining the temperature and in enhancing sports performance.

Key-Words: Pos-warm-up; Garments of heating; Sports performance