Università Degli Studi Di Milano

SCUOLA DI SCIENZE MOTORIE

Dipartimento di Scienze Biomediche per la Salute

Scuola di Dottorato in Scienze Morfologiche, Fisiologiche e dello Sport

Corso di Dottorato in Scienze dello Sport XXVIII Ciclo

POWER AND ENDURANCE CYCLING PERFORMANCE: THE KINESIO-TAPING APPLICATION AND THE INFRARED THERMOGRAPHIC ASSESSMENT OF MUSCULAR EFFORT

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Triennio accademico:
2013-2015

ABSTRACT

The present thesis has been written incorporating two different research lines involving the use of kinesio taping (KT) and the infrared thermography technology (IRT) in the field of physical exercise and performance analysis. Both topics are related to the involvement of cycling pattern in a laboratory environment assessing the role of skin behavior in terms of promotion (indirect) of muscle contraction and thermoregulation b KT and IRT, respectively.

The aim of this study was to determine whether the use of kinesio taping (KT) was helpful in increasing maximal-intensity cycling exercise. Sixteen active healthy subjects were enrolled in a randomized placebo, repeated measures design. All subjects were tested on a cycle ergometer under three conditions: without taping, taping along anterior thigh muscles, and sham taping across the same muscle groups. Results showed a significant increase in peak power output and total work after the longitudinally application compared to the condition with no tape applied ($p<0.05$). No significant difference was found between the two modes of application. Our findings indicated that the tactile stimulation of KT applied longitudinally provided positive effects during a sprint cycling performance in healthy and active subject.

The aim of the second study was to assess skin temperature and pedaling imbalance in response to maximal incremental exercise in elite cyclists. Ten competitive elite cyclists underwent a cycling incremental test to exhaustion. Kinetic variables, such as peak crank torque and asymmetric index (AI) were taken into account for propulsion and recovery phases at the beginning and at the end of the test. Thermal images of the thighs' frontal surfaces (captured by infrared thermography, IRT) were recorded before, immediately after and 3 and 6 min after the end of exercise. Cyclists showed a certain degree of symmetry in skin temperature presenting a significant reduction at the exhaustion point for both lower limb. As regard bilateral peak crank torques, a significant interaction was found in the propulsive phase across the time, even though the AI was < 10%. However, in the recovery phase, a remarkable value of AI > 10% was reported. Elite competitive cyclists showed bilateral asymmetry between propulsive peak crank torques in a state of extreme fatigue (i.e. at the exhaustion) with a low value of AI. On the other hand, skin temperature dynamics, measured by IRT, presented a certain degree of symmetry in both right and left limb in response to maximal incremental test. Future studies are need to determine the effective usefulness of IRT to monitor bilateral force asymmetry.

Keywords: muscle power; strength; muscle activity; pedalling; skin temperature

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PREAMBLE

The present thesis has been written incorporating two different research lines involving the use of kinesio taping (KT) and the infrared thermography technology (IRT) in the field of physical exercise and performance analysis.

The involvement of KT and IRT derived from two different approaches. As regard KT, before starting my PhD course, I was fascinated by the application of this particular tape over the skin to provide therapeutic treatments. I had seen several athletes wearing such tapes and my questions, based on the simple observation, led me to deepen in a scientific manner. After reading a conspicuous part of the scientific literature (KT-related), I realized what I would have liked to study. Accordingly, my proposal to apply for the PhD course was related to the investigation of KT effects within physical exercises in healthy people. After a long period of setting and data collecting, my research group and I started the experiment and, finally, our enormous work allowed us to reach a publication in the *Research in Sports Medicine*.

Together with the KT research project, my course allowed me to experience with the use of infrared thermography to assess how skin temperature behaves in response to exercise. Previously, my colleague Damiano Formenti (PhD) had already occupied to study skin temperature dynamics, measured by IRT, publishing three articles. Then, under the guidance of my supervisor Giampietro Alberti (Professor) and in collaboration with the Department of Physics with Nicola Ludwig (PhD) and Marco Gargano (MSc), I started to work with them. The first study we addressed was linked to the investigation of cutaneous temperature evolution during a squat exercise with two different speeds of execution (i.e. 1

s and 5 s). Our hypothesis was that the slower one would have produced a delay in the temperature response. After this study, I started an internship at the MAPEI center under the supervision of Ermanno Rampinini (PhD). I was willing to learn as much as possible within the cycling performance and analyses. Thanks to this cooperation, my research group and I decided to merge our competence in the IRT to those acquired in MAPEI with the help of Ermanno and Andrea Bosio (PhD). Therefore, after a profound literature revision, we formulated a project based on the use of IRT to study the occurrence of pedaling asymmetry in response to a maximal endurance cycling performance.

In this thesis, the idea to insert heterogeneous scientific contexts was born by the need to highlight those scientific experiences such teamworking and networking skills that allowed myself to improve as a researcher within the PhD course. However, as reported in the title, the present topics contains some commonalities that pass through the involvement of a specific performance task: "cycling".

I read dozens of articles concerning cycling outcomes and its assessment by cycle ergometers inside a laboratory. I learned the importance of using instrumentations (i.e. cycle ergometer) that can mimic various types of performance (e.g. sprint and endurance) in a controlled and suitable environment. Indeed, the peculiarity of testing pedaling motor task is that allows sport scientists to monitor humans' performance under standardized conditions, which is a mandatory prerequisite for obtaining reliable and valid measurements of any outcomes.

Another factor that unites the two topic discussed in the present thesis is the (indirect) measure of the skin responses during exercise. The application of KT and the involvement of infrared thermography (IRT) make use of the body skin as a means to determine or observe physiological outlines. When the tape is applied over a muscle course, the portion of the skin immediately below undergoes continuous stimulations, which may affect proprioception, lymphatic and cutaneous circulations, and afferents of specific receptors (Kase K., Wallis J., & Kase T., 2003). With the regard to the IRT, during an exercise, even moderate or intense, the body generates heat that has to be dissipated to the external. One of the most important mechanism of heat loss in humans is the evaporation that occurs throw sweating. As the sweat absorbs thermic energy, it evaporates over the skin transferring the body's heat to the air. In this context, cutaneous circulation and skin surface play a crucial role in the body thermoregulation, which is determinant during exercise. In this context, the IRT technology is capable to detected skin temperature and its evolution mediated by thermoregulation processes.

In view of that, although my main research focused on two diverse topics, I wanted to keep similar elements that could turn in a common thread within my personal scientific expertise.

ACKNOWLEDGMENTS

I would like to thank lot of persons, whom were important for me and that continue to be.

Due thanks are dedicated to my family, Mom, Dad and my older Brother for their presence, comfort and support without whom I would not have any hope of succeeding.

Special thanks are reserved to my supervisor Prof. Giampietro Alberti. Besides helping me constantly, he has always believed in me providing the chance to take part in the PhD course. Many many many thanks PROF!

During my course I have met extraordinary colleagues that proved to be simply FRIENDS. Luca, Damiano, Alessio, Luca, Gabriele, Christel, and Enrico. Thank you so much GUYS!!!!

I would like also to thank Prof. Michielon for his lighting tips. I have learned about problem and opportunity.

Many thanks to all professors and researchers with whom I had the good fortune to work and learn a lot of scientific insights: Nicola Ludwig, Marco Gargano, Marcello Iaia, Fabio Esposito, Andrea Caumo, Ermanno Rampinini, Andrea Bosio, and Zoran Milanovic.

Dulcis in fundo, I want to say THANKS to all my close friends that continue to be my LIFELINE! Thanks to Andrea, Stefano, Emanuele, Luca, Francesca, Michela, Andrea, and Romano.

Le persone speciali arrivano in punta di piedi; ma quanto rumore nell'anima quando se ne vanno….

A te,

"E' un altro giorno che trasforma e tutto intorno cambia forma

E' un altro luogo, è un altro modo, è un'altra chance che non ritorna

E non mi chiedo se bisogna o meno aver buona memoria

So soltanto che i ricordi a volte fanno mancar l'aria

Ciao ALE…

PUBBLICATIONS

All of the scientific work (peer-reviewed journal) I have produced during my PhD course is listed below:

- Formenti D., **Trecroci A.**, Cavaggioni L., Caumo A., Alberti Giampietro. Heart rate response to a marathon cross-country skiing race: a case study. *Sport Science for Health* (2014) 11, 125-128.
- **Trecroci A.**, Cavaggioni L., Caccia R., Alberti G. Jump rope training: balance and motor coordination in preadolescent soccer players. *Journal of Sports Science and Medicine* (2015) 14, 792-798.
- **Trecroci A.**, Formenti D., Rossi A., Esposito F., Alberti G. Acute effects of kinesio taping on a 6-s maximal cycling sprint performance. Submitted to the *Research in Sports Medicine* (ACCEPTED).
- Milanović Z., Sporis G., James N., Trajkovic N., Ignajatovic A., Sarmento H.,**Trecroci A.**, and Borges Mendes B.M. Physiological demands, morphological characteristics, physical abilities and injuries of female soccer players. Submitted to the *Journal of Human Kinetics* (MINOR REVISION).
- **Trecroci A.**, Milanović Z., Frontini M., Alberti G. Pre-planned agility, vertical jump and sprint performance in under 15 elite and sub-elite soccer players: a multivariate approach. Submitted to the Research in Sports Medicine (UNDER REVIEW).
- **Trecroci A.** Milanović Z., Rossi A., Broggi M., Formenti F., Alberti G. The effectiveness of SAQ training on physical performance and reactive agility in young soccer players. Submitted to the *Journal of Sports Medicine and Physical Fitness* (UNDER REVIEW).
- Formenti D., Ludwig N., **Trecroci A.**, Gargano M., Michielon G., Caumo A., Alberti G. Dynamics of thermographic skin temperature response during squat exercise at two different speeds. Submitted to the *Journal of Thermal Biology* (UNDER REVIEW).
- Cavaggioni L., Caumo A., Tosin M., **Trecroci A.**, Iaia F.M., Alberti G. A novel dry-land training of an elite paralympic swimmer: a case study. Submitted to the Research Quarterly for Exercise and Sport (UNDER REVIEW)

Below are also presented the overall scientific contribution related to the topics of the present thesis discussed in the form of abstract or poster presentation:

- Formenti, D., Ludwig, N., Gargano, M., **Trecroci, A.**, Caumo, A., Alberti, G.. Skin temperature modifications during physical exercise measured by infrared thermography. *Annual Meeting of Young Researchers in Physiology*. Anacapri. 2013

- **Trecroci A.**, Formenti D., Esposito F., Alberti G. Acute effect of Kinesio-Taping on 6-s maximal cycling sprint in healthy active people: a pilot study. *Book of Abstracts of the 19th Annual Congress of the European College of Sport Science*. Amsterdam, July 2014. Mini-oral communication.
- Formenti, D., **Trecroci, A.**, Ludwig, N., Gargano, M., Caumo, A., Alberti, G. Thermographic skin temperature response to different movement velocity of squat exercise until exhaustion: a preliminary report. *Book of Abstracts of the 19th Annual Congress of the European College of Sport Science*. Amsterdam, July 2014. Mini-oral communication.
- Ludwig, N., Formenti, D., **Trecroci, A.**, Gargano, M., Alberti, G.. Comparison of Image Analysis Methods in Skin Temperature Measurements during Physical Exercise. *Proceedings of Quantitative InfraRed Thermography (QIRT) Conference*. Bordeaux. 2014
- **Trecroci, A.**, Rossi, A., Formenti, D., Esposito, F., Alberti G.. Effects of a task-specific warm-up on a single-sprint cycling performance. *VI Congresso Nazionale della Società Italiana delle Scienze Motorie e Sportive (SISMES)*. Napoli. 2014
- Gargano. M., Ludwig N., **Trecroci A.**, Formenti D., Bosio A., Rampinini E., Alberti G. Skin temperature dynamics during an incremental maximal test in elite male cyclists. Abstracts submission at the *13th Advanced Infrared Technology and Applications Congress*. Pisa, Settembre 2015.
- Formenti D., Ludwig N., **Trecroci A.**, Rossi A., Fernandez-Cuevas I., Gargano M., Caumo A., and Alberti G. Has the kinetio tape a thermal effect on sprint cycling performance? A thermographic study. *Proceedings of Quantitative InfraRed Thermography (QIRT) Conference*. Gdansk. 2016

PART 1.

1.1. THE KINESIO TAPING METHOD: a general overview

The Kinesio Taping Method (KT) was introduced by a Japanese chiropractor named Dr. Kenzo Kase in 1979 (Kalron & Bar-Sela, 2013) in order to provide an alternative way for managing within clinical conditions (e.g. rehabilitation, musculoskeletal dysfunctions). KT method consists of a specific elastic adhesive tape to apply on the skin surface along the course of muscles, around the body joints and over specific skin's areas. The tape is capable to sustain the fascia, muscles and joints allowing limbs moving with an unrestricted range of motion (ROM). Its popularity has increased after the Seoul Olympics in 1988 becoming of great interest nowadays.

In the scientific literature, the number of publications related to the use of KT have also been increasing dramatically in the past seven years. For example, considering all of the papers published in journals indexed in PubMed, there has been an exponential increase from 2008 to 2015 of papers that incorporated specific keywords such as "kinesio tap*" or "kinesiotap*". Accordingly, the figure 1 shows clearly the size of this trend.

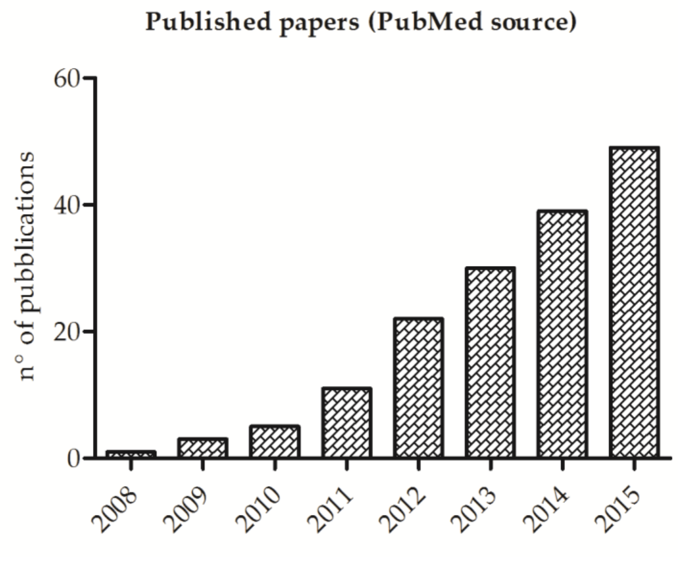


Figure 1. *The trend of the KT-related papers published in journals indexed in PubMed from 2008 to 2015.*

Chiropractors, physiotherapists, strength and conditioning professionals represent the main protagonists who involve the KT application for different aims and goals making such alternative method useful not only in clinical practices but also within sport sciences contexts.

1.1.1. Characteristics of the tape

The KT method involve a typical adhesive tape, which is produced expressly to mimic the approximate thickness and weight as well as elasticity of skin (Kase K. et al., 2003). The tape can be stretched up to 30% to 40% of its base length consenting a comfortable application (Figure 2). An original tape roll is produced with pre-existent tension applied to the paper underneath, which ranges from 10 to 15%, Further, to prevent and preserve the adherence of the tape during diverse physical activities (e.g. cycling, running, walking, and static postures) and intensities (low, moderate and high), it also possesses the following properties:

- Latex-free;
- 100% heat-activated acrylic glue adhesive;
- 100% cotton fibers;
- Water-repellent.

All of these properties allow the tape to be worn until five days without the need for reapplication.

In addition to the aforementioned characteristics, once it is cut, the tape comprise specific parts that must be taken into account during the application (Figure 3) (Nunes G.S., De Noronha M., Cunha H.S., Ruschel C., & Borges Jr. N.G., 2013). It is constituted by the right and left anchors, and the middle-base. The anchors represent the end portions of the tape applied with no tension at the origin and insertion points of muscles. Anchors have the aim to favor the KT action over the treated area. While the middle-base of the tape represent the portion actively involved in the KT action, the tension of which can be modulate related to the therapeutic aim.

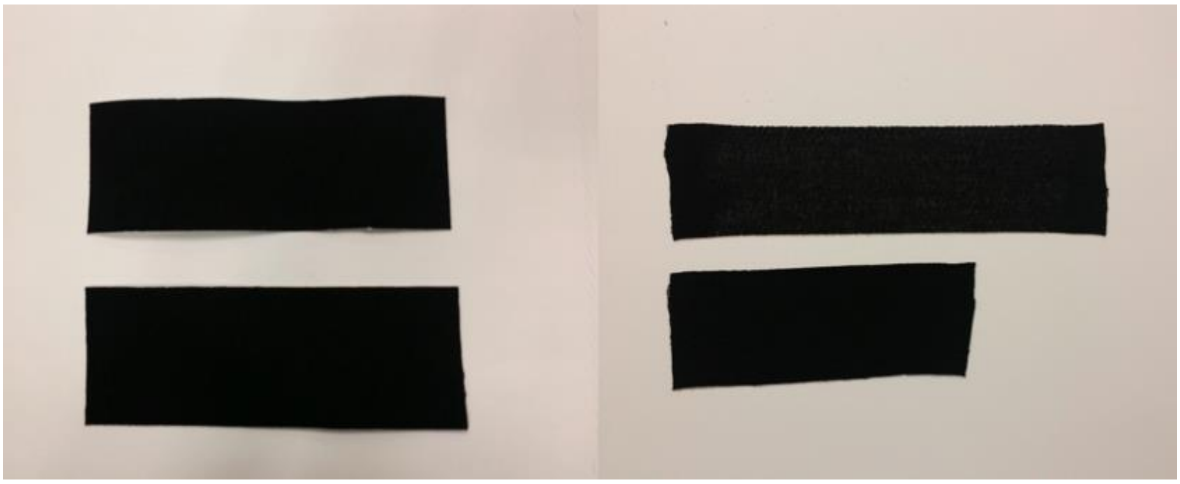


Figure 2. *The comparison between two identical strips: a strip with no tension applied – tape a) – and a strip with 100% of tension applied – tape b). Retrieved from: http://footballmedicine.net/kinesio-taping-in-sports/*

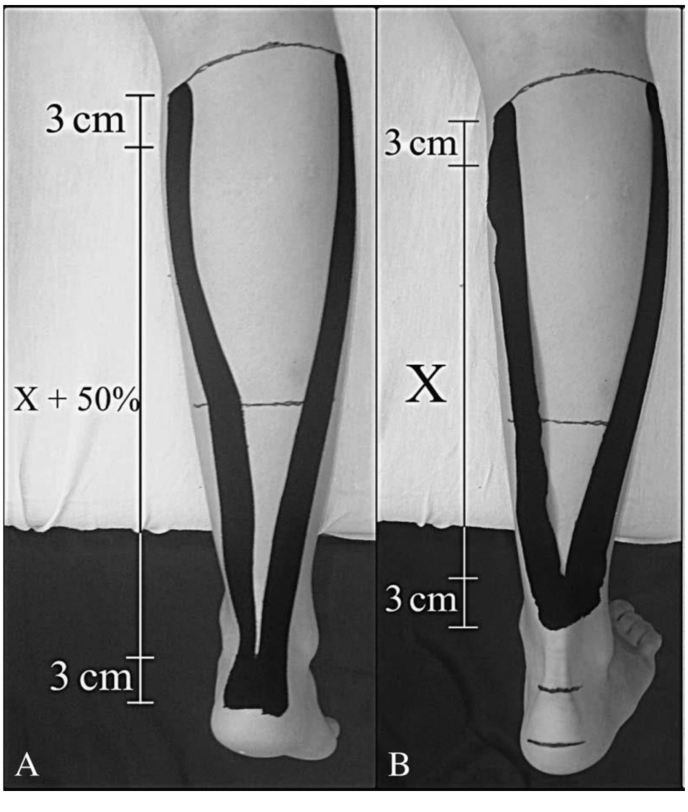


Figure 3. *The two images represent a KT application process in which anchors (3 cm) and middle base (X) parts are taken into account. In this case, a 50% of tension is applied in correspondence of the X (Nunes et al, 2013).*

1.1.2. Mechanisms of action

The application of KT over muscles bellies can promote various effects that depend on the way the taping is positioned and acts on the skin surface. Most of the authors who focused their research on the KT behavior agree in recognizing well-defined several effects during its usage (Csapo & Alegre, 2014; Fu et al., 2008; Gómez-Soriano et al., 2014; Kalron & Bar-Sela, 2013; Kase K. et al., 2003; Lumbroso, Ziv, Vered, & Kalichman, 2014; MacGregor, Gerlach, Mellor, & Hodges, 2005; Stedge, Kroskie, & Docherty, 2012; Tobin & Robinson, 2000; Vithoulka I. et al., 2010; Yoshida & Kahanov, 2007). According to Morrisey D. (2000), the main physiological effects can be summarized as follows:

- inhibition of overactive synergists or antagonists;
- facilitation of underactive movement synergists;
- promotion of proprioception;
- support and optimization of joint alignment;
- offloading irritable neural tissue;
- relief and reduction of pain associated with movement.

On the other hand, the actual physiological mechanisms, which are the basis on the above effects lists, have not been elucidated yet. To understand how those effects being produced, firstly, it is of primary importance to clarify how the tape acts over the skin surface and, consequently, its mechanical effects. Once it is applied with a certain lengthening, the tape (i.e. middle-base) tend to stretch and drag inversely the underlying tissue toward a specific anchor. Precisely, if KT is applied from the origin the insertion (i.e. proximal to distal) of a muscle, the tape acts recoiling to the origin site. This effect is known with the name of "recoil effect" (Parreira, Costa, Hespanhol Junior, Lopes, & Costa, 2014; Thelen, Dauber, & Stoneman, 2008). Such effect creates convolutions on the superficial layers of the skin that, according to the creator (i.e. Dr K. Kase), are capable to lift the skin favoring cutaneous blood and lymphatic circulation. For example, in case of lymphatic disorders (e.g. lymphedema), lymphatic fluid is poured in the interstitial space causing swelling (Kalron & Bar-Sela, 2013). In view of that, KT is believe to lift the skin increasing the space with the muscles, and, therefore, reducing pressure within the interstitial tissue. As a result, the accumulated fluid (i.e. exudates) is conveyed to the nearest lymph duct.

Furthermore, in accordance with several authors, the recoil effect is supposed to alleviate muscle weakness, hence, to facilitate muscle contraction (Alexander, McMullan, & Harrison, 2008; Konishi, 2013; Morrisey, 2000). It seems that the stimulation of cutaneous afferents throw tape application would drive to a change in muscle activity (MacGregor et al., 2005).

1.1.3. Scientific research based on kinesio taping principles

Within the last few years, despite the increasing interest in the KT method, a little number of studies have tried to verify how the tape directly behaves in both healthy and non-healthy subjects. Most of the research have focused their attention on the KT effects provided indirectly, thus, clear evidences about the mechanism of action are still inconsistent. The main primary effects (direct effect), which have been investigated, refer to the following topics: **1)** *proprioception* (Morrisey, 2000); **2)** *fascia unloading* (O'Sullivan & Bird, 2011); **3)** *motor neuron conduction velocity* (Lee et al., 2011).

1) Proprioception is defined as a complex sensation (perception) that derives from physiological information. According to Morrissey D. (2000), the integration of cutaneous receptors, muscle, fascia, tendons and joints with visual and vestibular input allow perception of position of sense (static), kinesthesia (dynamic) and force detection. Likewise, from a practical point of view, other authors reported that, in the case of joint perturbation, the processes attending to restore stability include mechanoreceptors stimulation, neural transmission, integration of the signals by the central nervous system, transmission of an efferent signal, muscle activation, and force production (Riemann & Lephart, 2002).

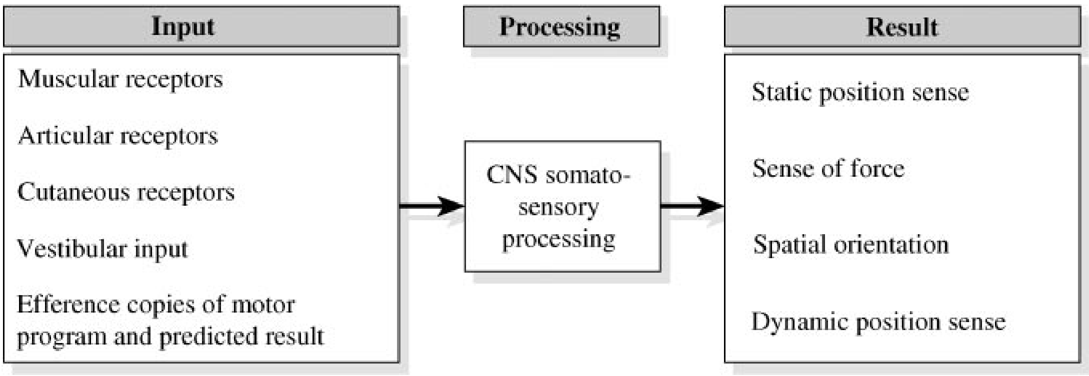


Figure 4. *Schematic representation of the proprioception process (Morrissey D., 2000)*

Taping is believed to be a form of proprioceptive biofeedback in which its degree of tension corrects any movements of a specific limb or body area occurring in non-desired position or plane (Morrisey, 2000). As a result, such tension would give a feedback for learning of give patterns of movement.

2) Fascia refer to a connective tissue wrapping and delimitating muscles, which have plastic properties. However, long-duration contraction/deformation of the connective tissue may lead to an increase of tension, thus, causing an impairment or fascia damages (e.g. fascia loading). Fascia unloading concept identify the reduction of tension within the fascia layers after a mechanical stimulus applied on the skin surface during movement. In this context, KT may play a key role in reducing mechanical stress (i.e. fascia unloading) on the tissue. O'Sullivan & Bird (2011) also claimed that the skin convolution occurred by KT application are responsible in lifting the skin unloading the underlying fascia, and consequently reducing pain.

3) Since the excitability of the central nervous system can be influence by tactile stimulation, it would be reasonable assuming that KT tactile input may sufficient to affect muscle power (Alexander et al., 2008). To measure this assumption, some authors aimed to investigate the motor neuron conduction velocity (MNCV) (Lee et al., 2011). An increase of such parameter would imply an increase in the motor neurons firing. The authors measured the MNCV testing radial, ulnar and median nerves at the same time with two conditions: with and without KT. Unfortunately, Lee et al. (2011) did not find significance differences in the latency, amplitude and motor nerve conduction velocity between with and without

KT. On the other hand, Konishi Y. (2013) demonstrated how KT stimulation was useful in rescuing actively the alpha motor neuron activity after taping. The author measured concentric and eccentric maximal voluntary contraction in combination of EMG during a leg extension exercise.

1.2. LITERATURE REVIEW IN CLINICAL PRACTICE

Firstly, to understand all of the potential aspects of this method, it is necessary to clarify deeply its role within the clinical literature. Since the KT was created as an alternative therapeutic method, over the last decade, it has been involved in various musculoskeletal injuries thanks to its effectiveness in reducing pain and inflammation, in improving range of movement and muscle impairment, and in supporting muscle, fascia, and joints (Kalron & Bar-Sela, 2013, 2013). Accordingly, numerous research have been investigated KT effects under clinical areas comprising some of the following main topics: patellofemoral pain syndrome, shoulder impingement and whiplash associated disorders.

Three main relevant studies have addressed the PPS by the use of KT with the aim to investigate the potential positive effects. Chen et al. (2008) recruited and tested 15 women with a diagnosis of PFPS (experimental group) and 10 healthy women (control group) to examine biomechanical variables during stair climbing. The protocol assessment included the analysis of ground reaction forces and EMG activity timing and ratio of vastus medialis and vastus lateralis under three conditions; with no tape in situ (nKT), with kinesio tape (KT) and with sham tape (ST) for all subjects. The authors reported significant differences between nKT and KT in the ground reaction forces outcomes for descending stair. Furthermore, a significant difference in the EMG timing and ratio was also reported between nKT and KT. As a result, the authors claimed that KT was useful to provide adequate balance between medial and lateral components assisting the patella movements and quadriceps muscles activation. On the other hand, Aytar et al. (2001) reported conflicting findings. They performed a double-blind study, which aimed to determine the acute effect of KT on pain, strength, joint position sense and balance in 22 female subjects affected by PFPS. The design incorporated an experimental group (n =12) and a control group (n = 10) tested in two different conditions: kinesio and placebo taping. Isokinetic quadriceps strength, joint position degree and balance index were measured before and 45 minutes after both applications. Significant differences were observed in quadriceps muscle between 60°/s and 180°/s, static and dynamic balance index scores before in the pre-post KT application. Likewise, significant differences between 60°/s quadriceps muscle strength and static balance index scores were also observed in the pre-post placebo application. Although KT induced to a significant increase in muscle strength and balance, such findings led the authors not to consider KT treatment an effective method in proprioceptive sensation compared to placebo condition. Lastly, Akbas et al. (2011) sought to verify the effect of 6 weeks of KT combined with classical exercises in the treatment of PFPS. A randomized controlled design was performed and 31 women (experimental group, n = 15; control group, n = 16) were tested for pain, flexibility and functional performance. The findings showed that the addition of KT to the classical exercises for reducing PFPS did not improve pain, but rather, it seemed to be effective in the hamstring muscle flexibility.

Other three studies have been taken into account in order to describe the KT main effects observed on shoulder impingement. In a first study were enrolled 17 baseball players affected by shoulder impingement and tested for 3-dimensional scapular motion, EMG of the upper and lower trapezius, and serratus anterior muscles (Huang, Hsieh, Lu, Su, & others, 2011). The design of the study included both KT and placebo conditions for all of the subjects. Since results showed an improved scapular posterior tilt at 30-60° in both groups, lower trapezius activity and strength increased only in the KT. A second study (Kaya, Zinnuroglu, & Tugcu, 2011), investigated the effects of a 3-day KT treatment on pain sensation localized over the shoulder. The authors reported that KT was useful to be an alternative treatment tool to alleviate pain in the immediate application. Lastly, a third study performed a randomized, double-blinded, clinical trials for repeated measure to determine any significant effects on shoulder pain and range of motion (Thelen et al., 2008). Thelen et al. (2008) reported that, although KT did not provided significant reduction in a pain intensity for shoulder impingement, it would be somehow useful to assist patients in improving their pain-free range of motion immediately after KT application on general shoulder pain.

A benchmark study dealt with the WAD issue measuring neck pain and cervical range-of-motion outcomes in 41 women randomly divided in two groups (GonzáLez-Iglesias, Fernández-de-las-Peñas, Cleland, Huijbregts, & Gutiérrez-Vega, 2009): kinesio taping group (KT) and sham group (SG). The subjects were measured immediately after the application and at 24 hours away. The authors demonstrated that KT exhibited significant improvements in pain levels and cervical range of motion immediately after the application and within the remaining 24 hours.

1.3. LITERAURE REVIEW IN SPORTS SCIENCES

In reference to the Sports Sciences context, it is taken into account specific studies that have investigated KT effects on healthy people or athletes to verify both potential therapeutic effects and performance improvements over specific muscle groups. Most of the studies investigating how KT acts in healthy people involved the lower limbs muscles, in particular the knee extensors, which play an important role in all of the locomotion forms. Accordingly, a recent meta-analysis selected 19 studies, of which 8 focused on quadriceps muscle group (QF) (Csapo & Alegre, 2014).

The actual aim of most of the studies involving healthy people or athletes is to verify the hypothesis that tactile stimulation provided by the KT would affect the neuromuscular system, thus promoting muscle contraction. It is reasonable to think that such hypothesis would appeal strength and conditioning professionals. Accordingly, one of the first study was published in the 2008 and aimed to investigate potential KT effects on muscle strength (Fu et al., 2008). The authors recruited 14 healthy subjects (7 males and 7 females) whom were tested for isokinetic concentric and eccentric peak force in a repeated measures design with the inclusion of three time conditions: no tape, immediately after application on rectus femoris (RF) and 12 hours after its application. After the entire experimental procedures, results did not show any differences among each condition, suggesting that KT effects on muscle strength were inconsistent. Likewise, Wong et al. (2012) attempted to investigate isokinetic muscular performance at 60°/s, 120°/s and 180°/s of both knee extensors and flexors. The authors taped 30 healthy subjects (14 males and 16 females) on vastus medialis (VM) within a repeated measures design, which included a condition with and without KT application. The authors did not find any significant alterations in the muscle peak torque and total work, however, they reported a significant shorter time to peak extension torque with the tape condition at all three angular velocities. According to the authors, such findings may suppose a somehow positive influence of the KT on muscular function.

Another study aimed to investigate isokinetic concentric and eccentric peak force at 60°/s and at 240°/s in 20 healthy females after KT application (Vithoulka et al., 2010). In this study, subjects were tested under three conditions: no taping, kinesio taping and sham taping. The use of a sham condition may represent a useful expedient to corroborate any actual changes in muscular performance after KT, allowing researchers to unmask probable psychological effects (Figure 5). In this case, the authors concluded their study reporting positive increase in the maximal eccentric torque during both concentric and eccentric contraction of QF. Accordingly, the latter findings suggest that KT application along the QF may be effective for those movements requiring eccentric activation.

Figure 5. *Sham taping.*

In contrast, Vercelli et al. (2012) did not found any differences in the isokinetic peak force of QF after application of KT on RF. In this study, besides a sham condition, the authors introduced another taping approach based on inhibition of muscle strength (Figure 6). As reported by Kase et al. (2003), when the tape is applied from the insertion to origin, it is supposed not to facilitate muscle contraction, but rather to inhibit it. Thirty-six healthy participants (17 males and 19 fermales) were involved in a single-blind, placebo-controlled crossover trial and evaluated for isokinetic maximal force at 60°/s and at 180°/s, single-leg triple hop and proprioception using the Global Rating of Change Scale (GRCS). Results demonstrated how, compared to the baseline, none of the three conditions exhibited differences in all variables assessed, even though, only some placebo effects in the GRCS were showed in all KT conditions. The authors also concluded that the KT effects on muscle activity should still be deeply investigated before promoting its usage.

Figure 6. *Inhibition KT application.*

From a practical point of view, outcomes from the aforementioned studies highlight obvious conflicting findings that do not clarify the actual role of the KT in enhancing muscle activity. Although, numerous hypothesis have been elaborated, there is still a lack of evidences. A reasonable explanation can be attributed to specific variables that range from

KT technique and muscle groups involved, to the fitness level of the subjects and protocol design. Up to now, they have been described studies that have involved only QF over a same performance (i.e. isokinetic force), however, there exists other research examining KT effects using different approaches in terms of muscles taped (Gómez-Soriano et al., 2014; Lumbroso et al., 2014; Nunes G.S. et al., 2013; Yoshida & Kahanov, 2007) and protocol design (Fratocchi et al., 2013; Lins, Neto, Amorim, Macedo, & Brasileiro, 2013). On the other hand, little is known about its effect on different types of performance involving explosive movements such as sprinting.

1.3.1. Power cycling performance

According to the principle of KT, its application is supposed to influence muscle contraction during sudden and explosive movements. Accordingly, as previously reported, several some authors focused their protocol on specific motor tasks, for example, referring to maximal leg extensions (Vithoulka et al. 2010) and vertical and horizontal jumps (Huang et al., 2011; Lins et al., 2013). However, in the case of the leg extension, there is a low specificity within the movement, which may not be comprehensive of sports dynamics. Furthermore, as regard vertical or horizontal jump tasks, the contribution of the upper limbs combined to the importance of the coordinative traits may influence the execution masking potential effects of KT.

In this context, the analysis of a pedalling task would be more suitable to delineate how the performance vary limiting such confounding factors. Moreover, the repetitive action within pedalling task is similar with the running style, which is a widespread movement in several sports and disciplines. Unfortunately, only two studies have addressed the KT effects involving a cycling task (Kim and Seo; Harmanci et al. 2015).

In the Kim and Seo's study, subjects were asked to perform an anaerobic cycling test (i.e. Wingate test) and an aerobic test (for determining VO_{2max}) on a cycle ergometer with the aim to assess if KT would produce effects in both power and endurance performance. Thirty subjects were taped on both quadriceps muscles and tested with and without the KT application. The authors revealed significant increase in the peak power and mean power of the Wingate test after taping, while no significant improvements were reported in the physiological and respiratory parameters (e.g. oxygen uptake, ventilation and heart rate). Harmanci et al. (2015) also involved a Wingate test to delineate the positive effects on power performance applying the KT on quadriceps muscles. Furthermore, they combined power measurements taken from 30 second-repeated jump. Thirty-one healthy subjects were located in two group: experimental and control group (with no KT in situ). Compared to the results of Kim and Seo (2012), the authors did not observe any improvements in the power parameters of the Wingate test, and they also found non-significant difference in the 30 second-repeated jump test.

Such conflicting findings may be attributed to the different design used in both study. On the other hand, the power performance analysed (i.e. Wingate test) by the authors may not be specific at highlighting potential positive effects of KT. In fatc, the Wingate test lasts 30 second, during which a subjects is required to sustain an all-out effort. However, the relative long duration of the test may be influence the peak power value that is being recorded in the first seconds of the effort. Since peak power is one of the most important variable in cycling to detect neuromuscular qualities, it would be worthy attempt to monitor if KT would able to affect it during a brief maximal sprint on cycle ergometer.

Preface to the first study

Since the mechanism of action is not clear, the use of KT and its effects should be broadened toward other forms of exercise based on explosive contractions. To date, only two studies have investigated the effectiveness of KT over sprint performance on a cycle ergometer, which represents a gold standard instrumentation to monitor and standardize a wide range of activities. The study I am going to show is a collaborative effort to address the aforementioned topic adding more information within the scientific literature of the sport science.

Acute effects of kinesio taping on a 6-s maximal cycling sprint performance

Abstract

Based on the hypothesis that tactile stimulation affects muscle activation levels, we theorized that taping vastus medialis and vastus lateralis muscles would improve a 6-s sprint cycling performance. Thus, the aim of this study was to determine whether the use of kinesio taping (KT) was helpful in increasing maximal-intensity cycling exercise. Sixteen active healthy subjects were enrolled in a randomized placebo, repeated measures design. All subjects were tested on a cycle ergometer under three conditions: without taping, taping along anterior thigh muscles, and sham taping across the same muscle groups. Results showed a significant increase in peak power output and total work after the longitudinally application compared to the condition with no tape applied ($p<0.05$). No significant difference was found between the two modes of application. Our findings indicated that the tactile stimulation of KT applied longitudinally provided positive effects during a sprint cycling performance in healthy and active subject

Introduction

Kinesio taping (KT) technique is commonly used to attain various therapeutic effects in rehabilitation, sport medicine and ultimately in enhancing athletes performance. Several studies investigated the possibility of KT to support joints functions (Yoshida & Kahanov, 2007), to elevate blood and lymphatic microcirculation in the subcutaneous tissue (Stedge, Kroskie, & Docherty, 2012), and to augment pain-relieving effect (González-Iglesias, Fernández-de-las-Peñas, Cleland, Huijbregts, & Gutiérrez-Vega, 2009; Merino-Marban, Fernandez-Rodriguez, & Mayorga-Vega, 2014). Nonetheless, other authors hypothesized that KT application could enhance muscle power and strength performance

(Fratocchi et al., 2013). The mechanisms through which KT bases its effectiveness on strength-enhancing potential have not been clarified completely. Some authors theorized that the application of KT over the muscle belly might induce a tactile stimulation capable to activate mechanoreceptors located deep in the dermis. Accordingly, this would influence the excitability of the fast and slow motor units, thus promoting an improvement in the rate coding of muscle force and in the muscle tone (Gómez-Soriano et al., 2014; MacGregor, Gerlach, Mellor, & Hodges, 2005). In this context, it can be reasonably hypothesized that anaerobic sport-related activities (e.g. sprint running, sprint cycling) could be positively affected by KT stimulation on specific muscles involved in the exercise. However, when compared to running, pedaling can be considered a representative motor task to assess sport-specific performance at maximal intensity with a well-controlled experimental condition (Neptune & Kautz, 2001).

Wingate Anaerobic Cycling test is the most popular anaerobic test used to determine the ability of athletes from various sports (e.g. team-sports players, cyclists) to perform an all-out effort in a laboratory setting (Aziz, 2004). However, shorter tests (e.g. 6-s sprint cycling test) are believed to better evaluate muscular functions of strength and power outputs with a greater involvement of specific muscle group recruitments (Akima, Kinugasa, & Kuno, 2005; Mendez-Villanueva, Bishop, & Hamer, 2007).

We hypothesized that the use of KT on specific muscle groups involved in a brief maximal cycling task would be beneficial in improving related-performance parameters. Therefore, the aim of the present study was to evaluate the immediate effects of KT application on the vastus lateralis and vastus medialis muscles during a single 6-s all out sprint on a cycle ergometer.

Methods

Subjects

Sixteen physically active males participated voluntarily in the study (age: 23.7 ± 1.9 years; body mass: 71.7 ± 9.7 kg; height: 1.80 ± 0.11 m). They had no history of musculoskeletal injury in the lower limbs within the year before the study. We considered the participants as physically active if they exercised a minimum of 3-days per week, with about 2-h sessions. The exercise routine of the participants involved different sports activities (e.g. tennis, soccer, basketball, and rugby) following a recreational aim. Participants were thoroughly informed of the protocols and procedures before their participation, and written informed consent was provided from them. In accordance with the Helsinki declaration as revised in 2013, the study was approved by the Ethical Committee of the local University.

Procedures

Each individual sprint was performed on the same friction-loaded Monark 894E cycle ergometer. The frictional force was generated by a belt sliding against a rotating fly-wheel and characterized by a basket holding the 10% of the total subject's body mass. The ergometer was interfaced with a computer by a specific software (Monark ATS software v. 3.3, Sweden) to display performance parameters and pedaling rate. Saddle height was arranged to ensure an optimal sitting position using the "heel method" (Peveler W. et al., 2005).

All participants were unfamiliar with cycle sprinting before the present research. To ensure a satisfactory reliability of the preliminary trials (McGawley & Bishop, 2006), they were asked to complete two familiarization sessions (F1, F2). The calculation of the Intraclass correlation coefficient (ICC) reported a high value of reliability for peak power (ICC = 0.949), for mean power (ICC = 0.965), and for total work (ICC = 0.971) between F1 and F2. Anthropometric characteristics were recorded at the beginning of the F1 for obtaining the measure of body height and weight. The preliminary sprint protocol involved participants to perform four 6-s sprint bouts interspersed by 3 min of passive recovery during familiarization sessions. The work done was recorded and the highest value was considered as the criterion score (Girard, Bishop, & Racinais, 2013). In the experimental trials (ET), participants were tested under three different conditions: without taping (nKT), with taping (both lower limbs: KT) and with sham taping (both lower limbs: ST). F1, F2 and ETs occurred at the same time of the day and were separated by a minimum of four days with a maximum of one week to avoid carryover effects (e.g. muscle fatigue, learning effects, potential residual effects of the tape after its removal). The order of the experimental trials was randomized using a random allocation table. The participants were advised to abstain from drinking alcohol and caffeinated drinks, and to refrain from physical activity involving lower limbs 24 h prior to testing.

Kinesio tape application

Standard two-inch (5cm) black kinesio taping (KT tex gold®) was used for all applications. The participants were asked to lay supine over a rigid table with the knee completely flexed and the thigh muscle stretched. Skin surface was prepared by removing hairs and drying the shaved area before the application. The tape was applied following the I-shape KT technique proposed by Kase et al. (2003) and utilized by Lins et al. (2013) on the vastus lateralis and vastus medialis muscles longitudinally, from the proximal to the distal portion, with 50% tension of the available length of the strip (Yeung et al., 2014). The strip was placed on the vastus lateralis from the greater trochanter to the lateral surface of the patella and on vastus medialis from the shaft of the femur to the medial edge of the patella (see Figure 1). After the application, the tape surface was rubbed to adhere the heat-sensitive glue. Participants were taped on the anterior thigh of the dominant side and bilaterally prior to the warm up. The same certified practitioner with profound knowledge of the KT method performed all of the applications.

Figure 2. *Kinesio taping application along the vastus lateralis and castus medialis muscles.*

Sham tape application

The ST protocol consisted of placing two I-shaped strip of the same kinesio tape applied with no tension. The strips were placed horizontally on the muscle bellies 5-cm above and 5-cm below the middle distance of the femur (Vithoulka I. et al., 2010) (see Figure 2).

Figure 3. *Sham taping application across the vastus lateralis and vastus medialis mucles.*

Experimental protocol

Prior to each experimental exercise, participants performed a task-specific standardized warm-up consisting of cycling for 4 min at a mechanical power 100 W, in which three bouts of maximal accelerations (approximately 2 s) at the end of the 2nd, 3rd and 4th min were performed. Before the experimental trial participants rested for 4 min. The main protocol involved participants to complete three 6-s sprint bouts interspersed by 180 s of rest. All sprints were performed starting with a moderate pedal cadence, from a seated position. Ten seconds before starting each sprint participants were instructed to increase pedaling rate around 80-85 rpm until the signal to start maximally. A countdown of 5 s was given to prepare subjects sprinting as fast as possible. To avoid bias from software sampling and to standardize the initial phase of the performance, the basket was set for fully dropping automatically at 100 rpm (Lunn, Zenoni, Crandall, Dress, & Berglund, 2013). A final "3-2-1-STOP" countdown was given toward the end of the bout. At the end of the sprint, the subjects remained seated on the bike for recovering between bouts. Vigorous verbal encouragement was provided during the trials. The sprint bout with the highest peak power output (PP) was considered in the analysis. Mean power (MP) and total work (TW) values of the same bout were also taken into account. The achievement of at least 95% of the criterion score was required in each individual sprint to prevent pacing effects and to ensure a good reliability among the experimental trials. If the criterion score was not attained, participants were asked to rest for a further 5 min and restart the bout (Girard et al., 2013).

However, this circumstance occurred on three occasions out of 144 trials.

Sample size determination

A preliminary study including five subjects was carried out to determine *a priori* data and a power analysis was used to detect the sample size. The minimal number of subjects required to achieve a power of 0.8 and an alpha level of 0.05 was calculated to be 9 subjects for peak power, average power and total work measures. To overcome a predicted drop-out of at least one third, the anticipated sample size has been increased to 17 subjects. However, only one person dropped out from the study during the experimental period.

Statistical analysis

Data are presented as mean ± standard deviation (SD). All the data met the assumption of normal distribution that was tested by Shapiro Wilk’s test. No violation of the assumption of sphericity was revealed by Mauchly’s test of sphericity. One-way analysis of variance for repeated measures (one-way ANOVA RM) with LSD post hoc comparison were performed to assess the difference among the conditions in each parameter. The proportion of variance attributable to each effect as well as the magnitude of the difference were estimated by partial eta-squared method (Part η^2). Statistical analysis was carried out using IBM® SPSS® Statistics (*version 21*, New York, U.S.A). A p value (*P*) lower than 0.05 was considered statistically significant.

Results

Values of each measure concerning sprint cycling performance outcomes are shown in Table 1. In the condition without tape (nKT), power and work values (expressed as a ratio standard with body mass) were the lowest compared to the conditions with the tape applied (KT and ST). Analysis from one-way ANOVA RM showed a significant difference in the PP ($F_{(2,30)} = 3.80$, $P = 0.034$) and TW ($F_{(2,30)} = 3.47$, $P = 0.044$) while no significant difference was found in the MP ($F_{(2,30)} = 1.46$, $P = 0.248$) between conditions. In particular, multiple comparison analysis revealed a significant difference between nKT and KT for PP ($P = 0.032$) and for TW ($P = 0.040$). No differences were found between KT and ST ($P > 0.05$) and between nKT and ST ($P > 0.05$).

Table 1. *Power and work outcomes of the 6-s sprint test among conditions.*

Outcome/Condition	nKT	KT	ST	ANOVA RM Part η^2
PP ($W \cdot kg^{-1}$)	12.44 ± 0.35	12.89 ± 0.29[a]	12.83 ± 0.26	0.200
MP ($W \cdot kg^{-1}$)	11.46 ± 0.34	11.90 ± 0.28	11.52 ± 0.31	0.089
TW ($J \cdot kg^{-1}$)	69.6 ± 1.99	72.30 ± 1.57[a]	71.36 ± 1.53	0.188

[a]*indicates statistically significant difference between KT & nKT (p < 0.05).*

PP = peak power; MP = mean power; TW = total work; nKT = no taping; KT = kinesio taping on the both lower limbs; ST = sham taping on the both lower limbs; Part η^2 = partial eta-squared.

Discussion

The main finding of the present study was that KT application on vastus lateralis and vastus medialis enhanced sprint cycling performance in healthy subjects. This result supported our initial hypothesis based on KT effectiveness in altering muscle lower limb during a maximal sprint-cycling task. Several studies observed similar improvements in isokinetic function on quadriceps femoris (Vithoulka I. et al., 2010) and on biceps brachii (Fratocchi et al., 2013), isometric function on wrist extensors (Kuo & Huang, 2013), and isotonic function on triceps surae (Huang, Hsieh, Lu, Su, & others, 2011). However, other studies failed to detect strength-enhancing potential of KT during a muscular effort (Fu et al., 2008; Nunes G.S., De Noronha M., Cunha H.S., Ruschel C., & Borges Jr. N.G., 2013; Vercelli et al., 2012; Wong, Cheung, & Li, 2012), and its beneficial effects have not been completely demonstrated.

It has been assumed that KT may increase muscle power and strength by tactile stimulation through a neuromuscular mechanism that involves an increase in the firing rate of motor units (Gusella, Bettuolo, Contiero, & Volpe, 2014). Hence, this relationship may be relevant for all sport activities based on brief maximal effort such as sprinting (i.e. running and cycling).

To the best of our knowledge only two studies managed to investigate the effects of KT on a maximal cycling task (Harmanci et al., 2015; Kim D.Y. & Seo B.D., 2012). In both studies subjects were asked to perform a 30-s Wingate anaerobic test (WAT) during which outcomes from anaerobic power and capacity (peak power and mean power) were recorded. In the first study, Kim et al. (2012) analyzed KT effects on each quadriceps muscle with a pretest-posttest design. After the KT treatment on quadriceps muscles, a significant increase in the peak power and mean power has been observed. In the second study, Harmanci et al. (2015) carried out a parallel group design in which the treatment group received KT on both rectus femoris, while no taping was given to the control group. Authors detected a small improvement (~2%) in the power performance after the taping application, but outcomes were not statistically significant. These discordant findings are probably due to the incongruence within the protocols in which are included omnifarious elements (e.g. tension of the tape, muscles taped), lackings (e.g. sham group), different exercise modes and performance assessments.

Compared to the present study, Harmanci et al. (2015) applied KT only on rectus femoris, however, during an all-out cycling effort, power output is primarily associated with the activation of vastus medialis and vastus lateralis muscles (Akima et al., 2005). Indeed, taping a single muscle may have produced an insufficient muscular stimulation capable to enhance cycling performance. On the other hand, positive findings reported by Kim et al. (2012) should be interpreted with caution. In fact, subjects were instructed to perform a WAT with no prior familiarization. Thus, it is conceivable that highlighted positive outcomes may be the result of an expected learning effect (Driller, Argus, & Shing, 2013), which is also confirmed by the lack of a randomization between experimental interventions. Additionally, the absence of a sham condition may constitutes a further limitation to the forcefulness of their conclusions.

Despite the use of a WAT provides the anaerobic power assessment, during 30 s of an all-out effort, the entire performance depends on for about one third of aerobic metabolism processes (Smith & Hill, 1991). Thus, variables such as total work may be mainly affected by subjects' training background, and consequently, possible KT effects may not be easily detectable. Contrarily, in the present research, power and work outcomes were evaluated by performing a single 6-s maximal sprint cycling in which aerobic system contribution is considered negligible (Mendez-Villanueva et al., 2007). Hence, since a sprint of 6 s is believed to depend strongly on the muscular activation, the 6-s maximal sprint cycling test may be reputed an accurate indicator of anaerobic power characteristics in humans (Mendez-Villanueva et al., 2007).

Another peculiarity of this study is the assessment of two different taping applications. Conventionally, it has been widely assumed that the tape facilitates muscle function when it is applied along the muscle belly, and vice versa, it is thought to inhibit muscle function when it is applied in the opposite direction or across the muscle belly (Tobin & Robinson, 2000; Vithoulka I. et al., 2010).

Accordingly, compared to the nKT, our findings revealed significant positive effects by applying strips in direction or longitudinally (KT) of vastus medialis and vastus lateralis muscles and inconsistent effects by applying strips across or horizontally (ST) bellies of the same muscle groups. However, no differences was observed between KT and ST. From a speculative point of view, a possible explanation may be related to an occurred psychological effect. In fact, despite the use of a tape with identical characteristics, positional variations between the appearance of the tape may have unmasked a placebo effect in the ST condition (Gómez-Soriano et al., 2014). On the other hand, we did not dispose for blinding methods to cover the treatment by participants and by the evaluator, thus further conclusions would be speculative.

Considering the large effect size provided by our analysis (see Table 1), it is reasonable to think that the use of KT applied along the thigh muscles should be preferred rather than applied across muscles bellies in improving a brief maximal cycling task in healthy subjects. Our study was conducted on physically active, healthy subjects with a moderate-to-good level anaerobic power. It is likely that the possible KT-induced improvement could be less masked/more effective in healthy untrained rather than in well-trained or highly-trained athletes in whom muscle functions have reached maximum levels.

Conclusion

This study sought to investigate possible effects of KT application on a maximal 6-s sprints cycling performance. Our results demonstrated that there are evidences supporting its effectiveness for improving sport-related activities with a short duration. The present research was limited to the evaluation of the immediate effects of the KT application during an individual sprint. Consequently, any potential delayed effects of the tape was not taken into account, even under a fatiguing protocol such as a repeated sprint test. Lastly, double blind protocols with different sham taping approaches are needed to achieve appropriate and objective scientific procedures.

PART 2.

2.1. BASIC ASPECTS OF THE INFRARED THERMOGRAPHY TECHNOLOGY

Every object is capable to emit infrared radiations and this intrinsic characteristic leads to be measured in an accessible way by infrared thermography, which is a technique to record images reporting a temperature distribution of that specific surface. All types of objects with temperature above absolute zero (0 °K) emit electromagnetic radiation and the intensity of this radiation is a function of temperature. Thus, there is a correlation between infrared energy and the temperature of the objects (R.D. Hudson, 1970).

The figure 7 shows three types of heat transfer in which is exhibited how an object exchange heat. In the case of infrared emission (IR), the heat is transferred directly from the surface of an object.

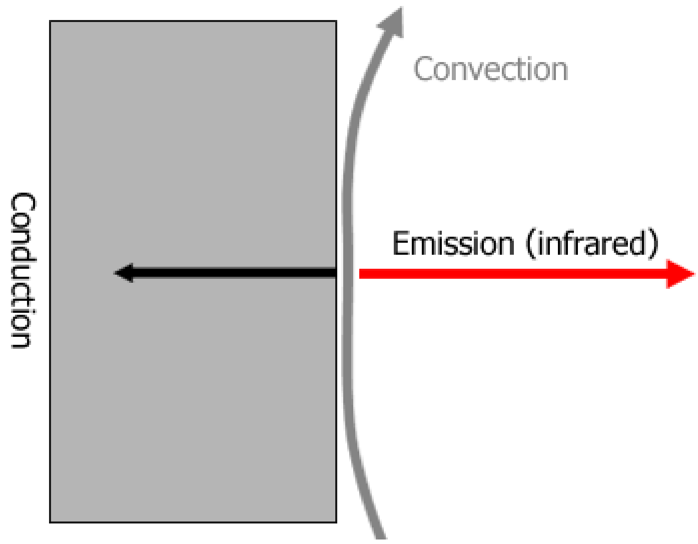


Figure 7. *Graphical example of infrared emitting features*

Conventionally, the band of this thermal infrared radiation lies within a range of 3 –14 μm (Figure 7).

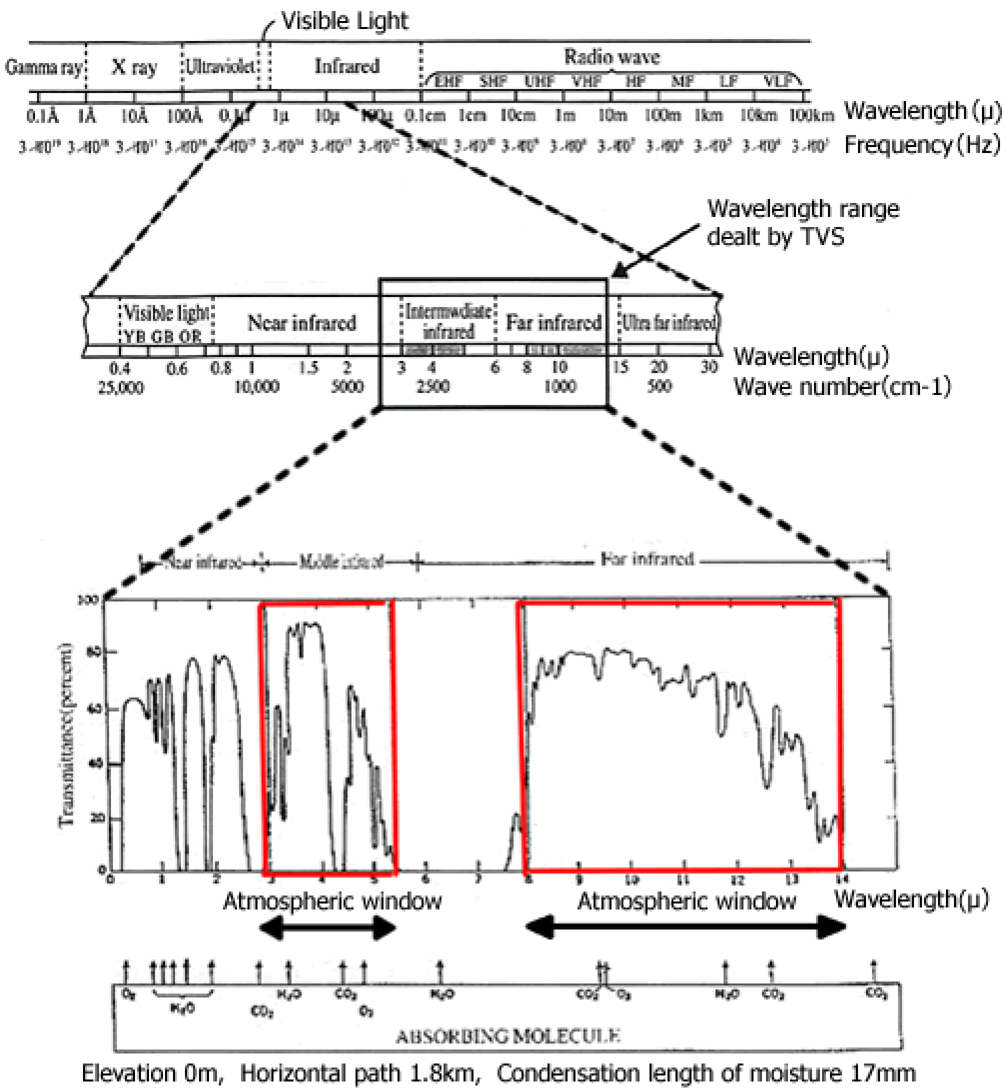


Figure 8. *Infrared spectral regions related to the wavelength range dealt by thermal vision sensors. Retrieved from: http://www.infrared.avio.co.jp/en/products/ir-thermo/what-thermo.html.*

Being a set of radiations, IR comprises various spectral bands that are defined considering the atmosphere transmittance ranging from 0.8 μm – 14 μm, which refer to the intermediate and far infrared designation (Figure 8). The effectiveness at emitting energy as thermal radiation is named emissivity (ε) and corresponds to the ratio of the thermal radiation from a surface to the radiation from an ideal black surface at the same temperature (Soib Taib, Mohd Shawal Jadin, & Shahid Kabir, 2012).

$$\varepsilon = \frac{W_{real\ body}(T)}{W_{black\ body}(T)}$$

Dissipation of thermal radiation, as mentioned at the beginning, can be observed by thermal vision sensors that characterize the thermal image cameras. In fact, such cameras generate images involving the thermal radiation distribution on the surfaces of specific objects (Skala et al., 2011). IR cameras have particular lenses, transparent that focuses the radiation onto a detector consisting of an array of elements (pixels). These elements, throughout different type of principle of detection, transform infrared radiation into electrical signal, which is further processed to generate a thermal image where any pixel represents a temperature value, and that can be yielded on a monitor (Blatteis, 1998).

Sensitivity and resolution are crucial variables in particular of medical aims. Cameras with focal plane arrays of 320x240 pixel, < 50mK of sensitivity and 25-50μm of spatial resolution can be an optimum setting to achieve thermal and spatial details (Skala et al., 2011).

2.1.1. Methodological principles

The ability of emit radiation of the human skin of 0.98 is comparable with that of a black body surface. However, the thermoregulation processes linked to the cutaneous behavior make difficult a clear interpretation of what thermal images outline (Blatteis, 1998). On the other hand, although thermal and spatial resolution has limited the quality of the measurements in the past, nowadays, a new generation of high-resolution cameras, advanced software and standardized protocols have been developed for biomedical application, resulting in improved diagnostic capability and reliability.

Infrared radiation emitted by a surface (e.g. skin) depends strictly on the experimental conditions such as moisture, airflow and surrounding temperature. As indicted by Ring and Ammer (2000), IRT can produce reliable results in medical application only when specific established rules and standards are followed (Ring & Ammer, 2000). The standards described by them involved the experimental protocol, examination room, control of temperature and humidity, subject information processing, imaging system, image acquisition, image processing and data analyses.

During thermography assessments, the tested person has to remain in a comfortable environment so that the mild thermal stress produced would result in vasoconstriction aided cooling of skin. Temperature and humidity of the examination room should also have to be controlled to prevent stressing conditionings such as shivering or perspiring. (J. D. Bronzino, 2006). Other methodological aspects refer to the restrictions from exposure to direct sunlight and uses of cosmetics, antiperspirants or deodorants immediately before the thermal assessment.

2.2. THE USE OF INFRARED THERMOGRAPHY IN BIOMEDICAL SCIENCES

As reported by Szentkuti et al. (2011), in clinical medicine IRT was used to assess breast cancer evaluating the temperature differences between the breast's skin surfaces above and not above the clinical tumor tissue. IRT is also used to monitor all of those conditions having a significant impact on the thermal homeostasis of determined body regions (e.g. circulatory and/or inflammatory disorders). The following pathologies represent the main clinical topics that have been underwent using IRT:

- rheumatoid arthritis;
- raynaud's disease;
- osteoarthritis of the knee;
- plastic and reconstructive surgery;

Furthermore, there are also other applications involving IRT in the field of dentistry and dermatology, diagnosis of rheumatologic diseases, detection of metastatic liver disease, heart treatment (Szentkuti et al., 2011).

During the last 20 years, considerable progresses have been achieved in the understanding of the physiological mechanisms of skin temperature changes and temperature distribution over surface of specific body area (Patterson, Warlters, & Taylor, 1994). Such progress provided a further boost in the thermography assessment applied to the biomedical sciences at studying not only additional clinical experiments but also scientific works related to the sport science fields.

2.3. THE USE OF INFRARED THERMOGRAPHY IN SPORTS SCIENCES

The use of IRT in the field of sports science indicates that chance to monitor skin temperature dynamics for assessing muscle recovery, designing training programs, examining effects of training, identifying potential edema, and evaluating muscle injuries (Neves et al., 2015).

The increasing application of IRT in such field can be attributed to the possibility at studying skin temperature responses to physical exercise with the aim to describe part of the thermoregulation processes (Szentkuti et al., 2011). Therefore, the analysis of infrared images recorded before, during and after sport-specific exercise would allow direct investigations of the skin temperature dynamics without an invasive approach.

The first studies focused not only on the skin temperature changes related to exercise, but also on the skin temperature distribution over the whole body, or specifics body regions. It has been found that during exercise, the evolution of skin temperature differed markedly from that observed before exercise (Monika Chudecka, 2013). This fact may be attributed to a redistribution of the blood flow under the cutaneous tissue, caused by intervention of thermoregulatory and non-thermoregulatory mechanisms.

Another issue is the study of the skin temperature variations associated to physical activity or exercise. It is possible to distinguish two types of thermographic investigation in exercise science:

1. Recording thermal images before and after a specific exercise, aimed to assess difference in skin temperature value from pre to post exercise.
2. Recording thermal images before, during, and after exercise, to evaluate the skin temperature dynamics occurred throughout a specific exercise.

Both types of investigation are present in literature. However, it is worth noticing that the second one (i.e. evaluating the skin temperature dynamics occurred throughout a specific exercise) present the greater difficulties in the preparation of experimental protocol and setting.

This is due to the body movement of the subject under inspection. It is not possible to move the thermal camera to follow the region of interest of subject during exercise. Thus, when region of interest coincides with parts of the body in movement, it is usually required that subject interrupts exercise for 1 s to 3 s or re-achieves the starting position (Formenti et al., 2013). Otherwise, it is possible to record thermal images in region of interests which do not coincide with parts of the body in movement (Zontak, Sideman, Verbitsky, & Beyar, 1998).

The ability to dissipate heat, related to the changes in skin temperature, may be influenced by exercise intensity, level of training and type of exercise. Accordingly, several studies have demonstrated that exists an unequal behavior in the skin temperature dynamics during prolonged exercise (Formenti et al., 2013; Merla, Mattei, Di Donato, & Romani, 2010; Patterson et al., n.d.; Torii, Yamasaki, Sasaki, & Nakayama, 1992). Formenti et al. (2013) investigated cutaneous skin temperature evolution in two groups of trained and untrained female athletes. The subjects were asked to perform a localized constant-load exercise (standing calf raise) for 2 min and calves body surface were involved in the thermal analysis. The authors observed a different behavior in the skin temperature evolution between groups, that is trained subjects responded to exercise more quickly than untrained peers. As a results, it was found that training level or experience may influence skin temperature dynamics in response to a localized steady-state exercise. Merla et al. (2009) involved fifteen trained runners to perform an incremental running test. They also chose specific body regions (e.g. trunk, thighs, forearm) to monitor with IRT at the beginning, during and after exercise. Results from their study showed an overall decrease in the skin temperature of trunk, thigh and forearm during a graded running test. The authors suggested that the continuous reduction in skin temperature assessed during the exercise was attributed to the vasoconstrictor responses, which were activated by an increase in catecholamine and other vasoconstrictor hormones linked to the incremental load. These studies observed answered several questions related to the skin temperature dynamics in trained and untrained subjects according to a constant load, or to evaluate skin temperature dynamics in trained subjects during an incremental load. Nevertheless, it would be worthy to understand if untrained and trained subjects differ in the same way in response to an incremental exercise intensity. Accordingly, Abate et al. (2013) analyzed cutaneous termic response in untrained and trained subjects analyzing trunk and upper limbs temperature surfaces during a submaximal incremental cycling test. As for Formenti's et al. study, the authors observed a significant different behavior of the cutaneous temperature between groups. However, Abate et al (2013) highlighted a significant reduction in temperature of the trained subjects compared to the untrained. This can also support the findings attained by Merla et al. (2013) in which a predominant vasoconstriction process underwent the continuous decrease of skin temperature. Furthermore, as compared to an untrained status, the training level influences thermoregulation mechanism favoring heat dissipation during an incremental cycling test.

Torii et al. (1992) was found earlier a clear fall in temperature in response to incremental cycling exercise anticipating that the reduction in skin temperature at the initial phase of the exercise was related to vasoconstriction mechanisms rather than evaporation due to skin sweat.

It is worthy notice that most of the aforementioned studies involved cycling tests to assess pre-selected phenomenon associated to the human performance (e.g. thermoregulation). The use of cycling test is justified by the fact that it is one of the most suitable testing approach undersetting a more practical standardization process.

In the specific case of thermoregulation assessment, thanks to its peculiarity, the involvement of a cycling test in a laboratory would be useful to investigate the actual relationship between increasing exercise intensity (in terms of incremental workload) and skin temperature dynamics.

2.3.1. Endurance cycling performance

It has been reported that along the increasing exercise intensity skin temperature tended to decrease for the entire duration of the effort (Abate et al., 2013; Merla et al., 2010;

Zontak et al., 1998) due to a predominant vasoconstrictor stimulus. These results were observed during both running and cycling incremental test, however, such studies did not focus their investigation to establish potential relationship between the increasing workload and thermoregulation processes. In view of that, a study has been involved in evaluating the relationship between skin temperature and muscle activation during incremental cycle exercise (Priego Quesada et al., 2015). The authors recruited ten physically active males, whom were asked to perform an incremental workload cycling test to exhaustion while muscular activation were recorded (by surface electromyography, EMG). There were taken into account four body regions: rectus femoris (RF), vastus lateralis (VL), biceps femoris (BF), and gastrocnemius medialis (GM). Thermal images were captured before, immediately after and 10 min after the cycling test. Their findings showed that participants with larger muscle activation levels presented lower increases in skin temperature after the test. This conclusion would suggest that those participants with a lower fitness level were less capable to dissipate heat from the skin surface analyzed. In support to this, significant inverse relationship were detected between changes in skin temperature and changes in the neuromuscular activation from VL, which is considered a primary muscle contributing to power production.

The study of Priego Quesada et al. (2015), however, did not show significant correlation between cutaneous temperature and peak power output (cycling performance) and this would also suggest that thermoregulation mechanism is related to the muscle activation rather than the mere performance. Other studies were conducted to explore the relationship between gross efficiency (GE) and muscular skin temperature of lower limbs in cycling (Bertucci, Arfaoui, Janson, & Polidori, 2013; Duc, Arfaoui, Polidori, & Bertucci, 2015). Gross efficiency is defined the ration of the power output to the metabolic power, which is in turn the total energy spent across to the time. This ratio is important because may be useful to identify how the heat accumulation, derived from exercising (e.g. pedaling), is being dissipate based on the difference between the energy consumption and the mechanical energy. Bertucci et al. (2012) observed an association between skin temperature and GE that is changes in GE values corresponded to changes in skin temperature.

Precisely, a lower value of GE referred to a higher decreasing of skin temperature for lower limbs. This implied that, as the work intensity increased, metabolic heat production improved eliciting thermal regulatory processes. Thus, such thermal processes result in a constant reduction of the skin temperature (Duc et al., 2015).

The important observations raised from the aforementioned research can clearly determine a direct association between muscle effort and skin thermoregulation processes detected by IRT. With this in mind, the use of IRT would be suitable to monitor changes in temperature of body surfaces covering active muscles expressing their degree of involvement during exercise (M. Chudecka, Lubkowska, Leznicka, & Krupecki, 2015).

2.3.2. Thermal asymmetry

An asymmetry commonly refers to an imbalance within specific characteristics (e.g. muscle activation) between two body sides. In literature, a number of studies have been investigated various types of asymmetry, from bilateral strength (Impellizzeri, Rampinini, Maffiuletti, & Marcora, 2007), running (Karamanidis, Arampatzis, & Bruggemann, 2003) and cycling (Rannama, Port, Bazanov, & Pedak, 2015). As far as the pedaling pattern task is concerned, most of the study focused on the evaluation of bilateral differences taking into account the forces applied to the crank, kinematic parameters and specific indexes of symmetry. (Bini, Diefenthaeler, Carpes, & Mota, 2007; Carpes et al., 2011; Bini, & Hume, 2014). According to these studies, pedaling asymmetry tend to decrease together with the increasing load, which would express changes in the muscle contribution to the effort.

On the other hand, asymmetry can be expressed as changes in temperature indicating the degree of similarity between two areas of interests (body surfaces)(Vardasca, Ring, Plassmann, & Jones, 2012). Several authors believe that IRT may be a useful tool to assess not only the evolution of cutaneous temperature behavior, but also to examine potential asymmetries between specific body surfaces (M. Chudecka et al., 2015; Uematsu, Edwin, Jankel, Kozikowski, & Trattner, 1988; Vardasca et al., 2012). Despite its potential functionality, there is an enormous paucity of studies assessing body asymmetry response to exercise using IRT.

Recently, a study sought to evaluate temperature changes of symmetric body surfaces over symmetrically activated muscles in athletes practicing two-oared rowing and handball, have the peculiarity to be symmetrical and asymmetrical, respectively. There were recruited 18 scullers and 16 handball players and tested before and after a regular training session. The front and back part of arm, forearm, trunk and thigh were taken into account for the IRT analyses of symmetry. Immediately after the exercise, the authors observed a decrease in the skin temperature for all subjects as reported also by other studies described in the earlier (Abate et al., 2013; Torii et al., 1992; Zontak et al., 1998). The novel findings, however, were related to non-significant differences showed between front and back areas of each body regions after the symmetrical exercise (i.e. two-oared rowing). Nevertheless, there were found statistically significant differences in the same areas of each regions in the handball player. Such results suggested that IRT was a useful non-invasive method to detect differences in the skin temperature dynamics response to exercise between symmetrical body regions. Furthermore, according to the Chudecka's et al. findings, bilateral changes in skin temperature where different after asymmetrical exercise rather than symmetrical exercise involving upper limbs.

In cycling, only a study have attempted to determine potential thermal asymmetry between symmetrical body sides (e.g. right and left limb) during a muscle effort. Arfaoui et al. (2014) recruited 11 cyclists derived from master category. They underwent an incremental submaximal cycling test during which calves bilateral calves region surfaces were monitored by IRT. The authors wanted to evaluate if IRT was able to predict muscle imbalance and to determine possible relationship between muscular skin temperature and heart rate. Results from this research showed that skin temperature of calves decreased in along with exercise intensity. Moreover, such decreased were not accompanied by an imbalance in the temperature evolution of each limb, indicating that both lower limbs behaved similarly in response to an incremental exercise. Finally, they also found a correlation between hearth rate and skin temperature suggesting further somehow association with cutaneous thermoregulation and exercise intensity (muscle activation).

Preface to the second study

Cycling asymmetry is an important aspect that has to be taken into account when assessing cycling performance, even though it is a result of symmetrical cycles of movement. I believe that the involvement of the cycle ergometer within laboratory setting is one of the most suitable approach to address the aim of the following research.

To date, none studies have attempted to monitor pedaling asymmetry in combination of the skin temperature evolution by IRT. The study I am going to describe, is the outcome of an important cooperation with three different institutional components: Department of Biomedical Sciences for Health (Università degli Studi di Milano), Department of Physics (Università degli Studi di Milano) and the Human Performance Lab (MAPEI).

Bilateral symmetry of crank torque and skin temperature responses to maximal incremental exercise in elite competitive cyclists

Abstract

Inter-limb force asymmetry commonly occurs throughout cycling performance linked to the exercise intensity. Due to the relationship between increasing muscle activation and cutaneous temperature, the present study aimed to assess skin temperature and pedaling imbalance in response to maximal incremental exercise in elite cyclists. Ten competitive elite cyclists underwent a cycling incremental test to exhaustion. Kinetic variables, such as peak crank torque and asymmetric index (AI) were taken into account for propulsion and recovery phases at the beginning and at the end of the test. Thermal images of the thighs' frontal surfaces (captured by infrared thermography, IRT) were recorded before, immediately after and 3 and 6 min after the end of exercise. Cyclists showed a certain degree of symmetry in skin temperature presenting a significant reduction at the exhaustion point for both lower limb. As regard bilateral peak crank torques, a significant interaction was found in the propulsive phase across the time, even though the AI was < 10%. However, in the recovery phase, a remarkable value of AI > 10% was reported. Elite competitive cyclists showed bilateral asymmetry between propulsive peak crank torques in a state of extreme fatigue (i.e. at the exhaustion) with a low value of AI. On the other hand, skin temperature dynamics, measured by IRT, presented a certain degree of symmetry in both right and left limb in response to maximal incremental test. Future studies are need to determine the effective usefulness of IRT to monitor bilateral force asymmetry.

Introduction

The assessment of bilateral asymmetry assumes a relevance not only in determining potential risks of injury and functional deficits of unhealthy people (Schmitt, Paterno, &

Hewett, 2012; Zwolski et al., 2015) but also in quantifying motor performance of healthy and athletes peers (Carabello, Reid, Clark, Phillips, & Fielding, 2010). Limb symmetry is considered a marker of physical performance (Tomkinson, Popović, & Martin, 2003) for both lateral (e.g. tennis) and bilateral dominant (e.g. cycling) sports, and consequently, between-limb differences may be counterproductive for the self-same performance outcomes.

In cycling, asymmetry refers to an imbalance and a disproportion in the force production of a leg compared to the contralateral within repeated cycles of pedaling. Although pealing represents a symmetrical motor task, cyclists often elicit a difference in the force application to the crank (Sanderson, 1990). Although it has been suggested that the presence of an imbalance within pedal forces production would limit cycling performance anticipating fatigue (Felipe P. Carpes, Mota, & Faria, 2010), only few studies have addressed bilateral asymmetry in cycling, and most of them reported differences in the kinetic variables (i.e. crank torques and pedal forces) and in the asymmetric index (AI).

On the other hand, bilateral pedal asymmetry may be also evaluated by the infrared thermography (IRT), which is a valid technique used wide-ranging in biomedical studies to evaluate human thermoregulation and its role on skin temperature (Ludwig, Formenti, Gargano, & Alberti, 2014). Recently, Priego Quesada et al. (2015) sought to assess the relationship between muscle activation (using surface electromyography) and skin temperature (using IRT) in ten physically active volunteers during an incremental cycling test. Temperature outcomes were obtained before, immediately after and 10 min after the test from four specific body regions. The authors observed a significant inverse relationship between temperature changes and neuromuscular activity. Hence, subjects with greater muscle activation exhibited a fewer increase in temperature at the end of the exercise (Priego Quesada et al., 2015). In view of that, being influenced by workload, the skin temperature assessment may provide worthy and valuable information about potential thermal asymmetries during exercise, especially in athletes (Chudecka, Lubkowska, Leznicka, & Krupecki, 2015).

According to the latter statement, Arfaoui et al. (2014) sought to investigate potential thermal asymmetry related to the increasing workload in master cyclists. Nevertheless,

although their results confirmed the inverse trend of the skin temperature profile toward the workload, non-significant bilateral changes were highlighted throughout the exercise. Nonetheless, in their study, the authors took into account only the thermal imbalance, while no right- to -left differences in the kinetic parameters were reported. We believed that a parallel assessment of thermal and pedaling symmetry would be worthy to delineate clearly any potential imbalance caused by an increasing exercise intensity in athletes.
Therefore, the aim of the present research was to evaluate skin temperature and pedaling imbalance in response to maximal incremental exercise in elite cyclists. We hypothesized that cyclists showing significant bilateral differences in the kinetic values (i.e. peak crank torque) should also present bilateral changes in skin temperature assessed by IRT.

Methods

Participants

Ten male elite cyclists participated voluntarily in the study. Their mean and standard-deviation values for age, body mass, height, body fat percentage, and maximal oxygen uptake were as follows: 21.40 ± 2.63 years, 68.85 ± 6.79 kg, 1.76 ± 0.39 m, 8.92 ± 2.44 %, 67.60 ± 5.37 ml/kg/min. According to the declaration of Helsinki, the study was approved by the Ethical Committee of the local University. A written informed consent including a complete description of procedures and potential risks was provided and signed by all the participants. They were also instructed to avoid high-intensity or strenuous physical activity 24-h prior to testing.

Procedures

Two experimental sessions were carried out one week apart at the same time of day (9.00 a.m. to 12.00 a.m.) during which all participants were tested. In each session, prior to testing, stature and body weight were recorded by a stadiometer and weighing scale to both the nearest 0.1 cm and 0.1 kg, respectively. Skinfold measurements of pectoral, arm, abdominal and thigh were also included together with waist and arm circumferences to estimate the body fat percentage. Afterwards, participants were asked to sit in a rest position without touching their legs on an isolating mat for a period of 10 min to acclimatize the body skin to the laboratory climatic condition (Marins et al., 2014) (temperature 22-23 °C; relative humidity 50± 5%; constant natural and fluorescent lighting and no direct ventilation). After the acclimatization period, they were instructed to mount on the cycle ergometer. A customized setting was used for each participant to replicate the position assumed on his own bike. Then, all thermal acquisitions were performed asking the cyclists not to pedal and staying upright with the leg extended toward the floor.

Kinetic data acquisition

Independent pedal force outcomes for both right and left crank were constantly measured by a built-in modified strain gauge technology mounted on the cycle ergometer (Lode Excalibur Sport, Lode B.V., Groningen, Netherlands). The force measurements occurred with a rotational resolution of 2° and an accuracy of 0.5 N. A PC was interfaced to obtain raw data for the analysis.

The overall pedal forces were collected during the last thirty cycles of the first workload stage (i.e. 100 W) and the last workload stage (i.e. exhaustion) of the maximal incremental test. Peak crank torques were recorded and taken into account for the downstroke (propulsion phase) and upstroke (recovery phase) movements of the entire pedal cycle. In the present study, propulsion phase was defined as the set of crank torques applied from 0° to 180° of a pedal cycle in clockwise direction, while recovery phase was defined as the set of crank torques applied from 180° to 360° of the same cycle in counter clockwise (Figure 1). Moreover, crank torques dynamics of both phases were reported to better represents each different behaviour (see Appendices). The asymmetry index (AI) was also considered to express right to left differences in both propulsion and recovery phases. To calculate the AI, it was used the equation proposed by Karamanidis et al. (2003).

$$AI\% = \left[\frac{|X_r - X_l|}{\frac{1}{2}(X_r + X_l)}\right] \cdot 100$$

were X_r refer to the parameter of the right limb and X_l refer to the parameter of the left limb. This equation provides an absolute asymmetric index, which is not affected by leg preference. The AI is being commonly used to quantify the between-limb cycling imbalance, wherewith any value higher than 10% corresponds to a significant pedaling asymmetry (Bertucci, Arfaoui, & Polidori, 2012; Felipe P. Carpes et al., 2010; F. P. Carpes, Rossato, Fari, & Bolli Mota, 2007).

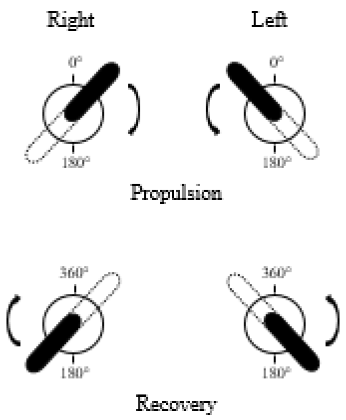


Figure 1. *Schematic representation of the propulsion and recovery phase according to the crank angle*

Thermographic data acquisition

Thermal images arising from the anterior surface of the participants' thighs were recorded by a 14-bit digital infrared thermo-camera (AVIO, TVS-700, 320 x 240 Microbolometric Array; 8-14 μm spectral range; 0.07 °C thermal resolution; and 35 mm lens). The thermocamera was placed directly in front of the cycle ergometer at the fixed height of 118 cm with a background at constant temperature. This setting allowed the infrared detector of the thermal camera to self-calibrate periodically using the background temperature as reference (Formenti et al., 2013). Recordings were implemented using a digital frame grabber setting to capture one image per 10 s. Two thermal images were captured at each specific time point: basal (before the warming up), starting point (after the warming up), exhaustion point, and post-exercise period (3 min and 6 min after the exhaustion). The overall temperature data obtained for each pair of thermal images were averaged and taken into account within the analysis.

All of thermal images were processed setting an emissivity factor of 0.97 and analyzed by the Tmax method, which was proposed by Ludwig et al. (2014). Tmax consisted of selecting one region of interest (e.g. muscle groups involved in the exercise) separately for the left and right legs. With a aid of a specific software (GRAYESS® IRT Analyzer, v. 4.8) there were selected 5 hottest pixel with a minimum of 5 pixels of distance among each other within each region (Formenti et al., 2013; Ludwig et al., 2014). Thus, an equal number of pixels were used to derive temperature values from targeted heat dissipation areas for the thermal images.

Protocol

The entire protocol of the study is shown in figure 2. After 10 min of warm up performed with a constant load of 100 W, subjects completed an incremental maximal cycling test of assessment maximal oxygen uptake and maximal power output. Each participant started at a workload of 100 W with an increase of 25 W every minute until exhaustion. Pedaling cadence were kept constant throughout the test in a range of 90 ± 3 rpm. Time to exhaustion point corresponded with the cyclist's incapacity to maintain a cadence above 87 rpm. Whereas, maximal power output coincided with the workload of the last stage fully concluded.

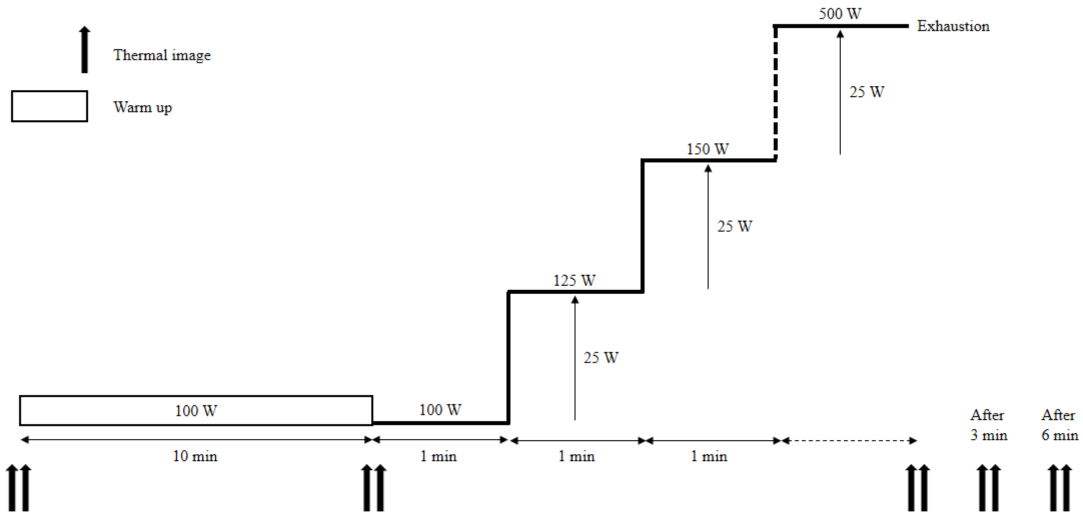


Figure 2. Protocol of the maximal incremental cycling test

Statistical analysis

The assumption of normality was verified by the Shapiro Wilk's test for each variable. Test-retest reliability was assessed for the skin temperature and kinetic data using a one-way intraclass correlation coefficient (ICC). A two-way repeated analysis of variance (two-way ANOVA RM) was used to compare skin temperature and kinetic values separately for each phase (propulsion and recovery) between right and left lower limbs across the time points (within-subjects factor). Partial eta squared (Part η^2) was used to estimate the magnitude of the difference as an appropriate measure of effect size for ANOVA (Richardson, 2011). The thresholds for a small, moderate and a large effect were defined as 0.01, 0.06, and 0.14, respectively (Cohen, 1988).

Effect size (ES) was computed to assess the meaningfulness of differences in the asymmetry indexes between propulsion and recovery phases at the initial and final workload of the incremental cycling test. ES was classified as follows: 0.20, 0.50, and 0.80, respectively (Cohen, 1988). An alpha threshold of $p < 0.05$ was set to identify a statistical significance.

Statistical analysis was performed using the IBM SPSS Statistics software (v. 21, New York, U.S.A.). Data are reported as mean ± SD.

Results

Figure 3 shows the average skin temperature data recorded for the right and left limb before and after the cycling test. Average right- to -left temperature difference detected by IRT were approximately 0.1, 0.15, 0.21, and 0.19 °C at the start point, exhaustion point, and 3 min and 6 min after the end of the exhaustion, respectively. No significant interaction was observed across the time points between right and left limb (P = 0.643, Part η^2 = 0.045). A significant difference was observed in the values of both limbs at the exhaustion point compared to those recorded before exercise and during the recovery period until the sixth minute ($F_{1,9}$ = , P < 0.0001, Part η^2 = 0.539). Right-left limb temperature values did not significantly differ to each other before, at the exhaustion and after the recovery.

Results of the two-way ANOVA RM revealed a statistically significant interaction (main effect) between limbs in the peak crank torques of the propulsion phase ($F_{1,9}$ = 14.813, P < 0.05, Part η^2 = 0.622), thus indicating that the right limb behaved differently compared to the contralateral (Table 1).

Peak crank torque differences were also found (simple effect) between the starting workload (i.e. 100 W) and the ending workload (i.e. at the exhaustion) for both propulsion (P < 0.0001, Part η^2 = 0.966) and recovery phase (P < 0.0001, Part η^2 = 0.854). No significant interaction was observed between the peak crank torques of the right and left limb in the recovery phase (P > 0.05, Part η^2 = 0.004). As compared to the initial workload stage (i.e. 100 W), consistent changes were found in the AI of the recovery phase at the end of the last stage (AI% > 10%, ES = 1.470), while unremarkable changes were found in the AI of the propulsion phases (AI% < 10%, ES = 0.213).

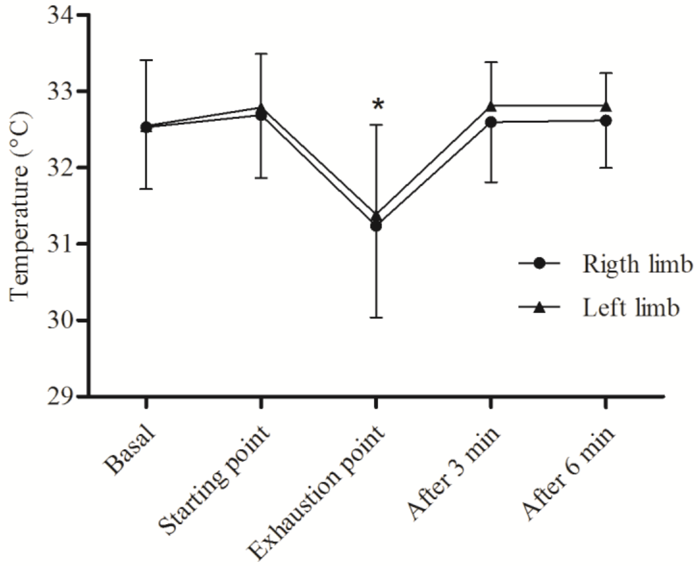


Figure 3. *Skin temperature dynamics of both right and left limbs across time points. Note: * Significant difference ($P < 0.05$) compared to all of the time points.*

Table 1. *Kinetics data of the initial and final workloads for both propulsion and recovery phases.*

Pedal cycle		Initial workload	AI %	Final workload	AI %	*P*
Propulsion	R	30.28 ± 3.84	7.94 ± 5.42	72.69 ± 8.35*	7.01 ± 5.95	0.004§
	L	30.90 ± 2.93		68.47 ± 8.19*		
Recovery	R	-16.35 ± 1.93	8.98 ± 7.41	-8.09 ± 4.35*	31.67 ± 21.76#	0.853
	L	-15.73 ± 1.60		-7.66 ± 4.76*		

§*Significant interaction ($P < 0.05$)*

**Significant difference ($P < 0.05$) in the within-subjects factor (initial and final workload) for each limb*

#*Evidence of asymmetry ($AI > 10\%$) in the recovery phases of initial and final workload*

R = right, L = left, AI% = asymmetry index, P = p-value

Discussion

The main finding of the present study was that as the cyclists fatigued, the propulsion phase of their pedal cycle elicited significant bilateral differences in the peak crank torques. On the other hand, right- and -left average skin temperature - measured by IRT- showed a similar behaviour without presenting thermal imbalance under fatigue.

To the extent of our knowledge, this is the first study that sought to evaluate bilateral thermal and kinetic symmetry in response to an incremental maximal test in elite cyclists.

With regard to the kinetic outcomes, Bertucci et al. (2012) found that master cyclists showed a significant bilateral asymmetry in the force applied to the crank at low- to -moderate workload during a submaximal incremental test. On the other hand, Carpes et al. (2007) have observed a decrease of bilateral asymmetry, quantified with the AI%, throughout a simulated racing condition (i.e. 40-km cycling time-trial) in amateur competitive cyclists. According to the authors, as the power output increased, pedaling pattern turned symmetrical to apply effective force to the pedals addressing a potential premature neuromuscular fatigue (Bini, Diefenthaeler, Carpes, & Mota, 2007; F. P. Carpes et al., 2007). However, this conclusion is partially supported by the kinetic outcomes of the present study. We observed that the average AI% of the propulsive phase was well below the threshold of 10% at the exhaustion (Table 1). Nevertheless, surprisingly, we found a significant difference in the propulsive peak crank torque between the right and left limb at the same condition ($P < 0.05$). This result was fairly unexpected, since significant crank force imbalance should refer to higher values of AI% between lower limbs (Felipe P. Carpes et al., 2010). Accordingly to the literature, it has been previously summarized that bilateral differences ranged from 5% to 20% depending on which variables are taken into account. With regard to the magnitude of propulsive crank torque, a conventional threshold of remarkable asymmetry was defined for AI greater than 10% (F. P. Carpes et al., 2007). However, we recorded a value of AI of about 7%. From a speculative point of view, this would indicate that highly-trained cyclists may exhibit significant asymmetry even when AI% is lower than 10%.

At the exhaustion, in the recovery phase, negative peak crank torques were similarly in both legs, whereas the average AI% presented values larger than 30%. It is likely that as cyclists fatigued their style of pedaling stroke turned compromised during the recovery phase (Sanderson & Black, 2003). This can be also explained by the fact that cyclists applied significant lower crank forces for both lower limbs compared to the initial workload stage. Consequently, this may have elicited an increase of force during the subsequent downstroke (i.e. propulsive phase) to overcome such reduction, as previously indicated (Sanderson & Black, 2003).

Lately, it has been suggested that potential imbalance expressed by specific body sides may also underlie an overload in muscle activation, which can elicit changes in the skin temperature surface covering the same body sides (Chudecka et al., 2015). This would provide further important insights of the degree of muscular involvement during physical activity, especially linked to inter-limb asymmetries.

During a continued physical activity, active muscles produce excess heat that has to be dissipated through the skin surface, avoiding an overly increase of internal temperature (Torii, Yamasaki, Sasaki, & Nakayama, 1992). At this point, via the activation of both vasoconstriction and vasodilatation mechanisms, blood flow is being drained from core districts to the superficial layers (i.e. skin) to transfer heat for thermal dissipation by sweating (Torii et al., 1992).

Skin temperature is supposed to be related to the muscular effort inasmuch as reflects the level of efficiency in eliminating excess heat. (Priego Quesada et al., 2015). In this context, the use of IRT has the advantage to measure heat radiation on skin surface with a non-contact approach, thus allowing sport scientists to monitor instantly the temperature of specific body regions linked to physical activity (Ludwig et al., 2014).

However, the ability to dissipate heat, related to the changes in skin temperature, may be influenced by exercise intensity, level of training and type of exercise. Accordingly, several studies have demonstrated that exists an unequal behavior in the skin temperature dynamics during prolonged exercise (Formenti et al., 2013; Merla, Mattei, Di Donato, & Romani, 2010; Torii et al., 1992). As compared to sedentary, Formenti et al. (2013) reported a faster increase in cutaneous temperature of both legs during localized constant-load exercise (standing calf raise) in female athletes. On the other hand, Merla et al. (2009) observed an overall decrease in the skin temperature of trunk, thigh and forearm during a graded running test in well-trained subjects.

The present data showed a significant fall (~1.5 °C, $P < 0.05$) of the average skin temperature of both limbs from the starting to the exhaustion point of the incremental test. Likewise, after the exercise, skin temperature returned rapidly (within 3 min) to the baseline and remained constant for the rest of the recovery period. Such skin temperature dynamics may be the results of an effective cutaneous thermoregulation, as a result of the competition between vasoconstrictor/vasodilator responses (Fritzsche & Coyle, 2000; Torii et al., 1992). Furthermore, fall in skin temperature, as well as its rising, occurred similarly for both lower limbs expressing a certain degree of thermal symmetry from the beginning to the end of the incremental exercise. In fact, average right- to –left imbalance detected by IRT varied approximately up to 0.20°C, which represents an unremarkable difference. In support to this, a benchmark of normal symmetry range has been previously determined (Vardasca, Ring, Plassmann, & Jones, 2012). Vardasca et al. (2012) summarized that a maximum value of 0.5 ± 0.3 °C between corresponding left and right sides of body extremities can be considered an acceptable asymmetric threshold (Chudecka et al., 2015). Likewise, Chudecka et al. (2015) investigated the thermal imbalance in symmetrical (rowing) and asymmetrical (handball) sports activities. Two groups of athletes were involved (scullers and handball players) and tested within a regular session in which they were asked to perform two-oared rowing and sport-specific endurance training (including actual elements of the game), respectively. There were compared and analyzed front and back areas of arm, forearm, thigh, and trunk regions. The authors observed a decreased in the mean temperatures immediately after the training in both groups. Furthermore, they observed statistically significant differences between front and back areas of arm and forearm in handball players. Whereas, scullers showed no differences between front and back areas temperatures compared to each body region. Although Chudeka's et al. (2015) protocol involved sessions with submaximal exercise intensity rather than maximal, their results was in line with our finding suggesting that symmetrical exercise (e.g. rowing as well as cycling) did not elicit remarkable asymmetry in the temperature of the skin above activated muscles, especially on frontal thigh's surface. On the other hand, based on the evaluation of bilateral asymmetry in cycling, the present kinetic data were not in accordance with the thermal outcomes attained by IRT. A likely explanation can be attributed to the effects of high exercise intensity (leading to fatigue) on central and peripheral thermoregulation mechanisms

(Fritzsche & Coyle, 2000). It has been reported that at high intensity, skin blood flow is dependent on core temperature. Indeed, a core temperature above ~ 38°C may prevents further increases in the cutaneous blood flow (Fritzsche & Coyle, 2000). Therefore, we could assume that the hypothesized increase in core temperature may have compromised cutaneous thermoregulation at the exhaustion point, thus influencing skin temperature dynamics related to potential thermal asymmetry. Unfortunately, the assessment of core temperature was beyond our primary purpose and further assumptions would be mere speculations.

Our findings, however, presented some limitations. A first limitation is referred to the fact that we analyzed bilateral symmetry in both thermal and kinetic outcomes at the beginning and at the end of the incremental exercise rather than throughout. Hereby, we cannot establish if skin temperature and peak crank torques of both limbs behaved symmetrically or not during low- to –moderate workloads in elite cyclists.

Another limitation refers to the lacking of a kinematic analysis in terms of an assessment of each limb motion pattern. Kinematic changes are supposed to be related to the change in the force to prevent reductions in performance. Hence, kinematic evaluation would be useful to provide greater support at describing reduced efficiency of the recovery phase linked to fatigue found in the present research, and its role on the subsequent force application during the downstroke.

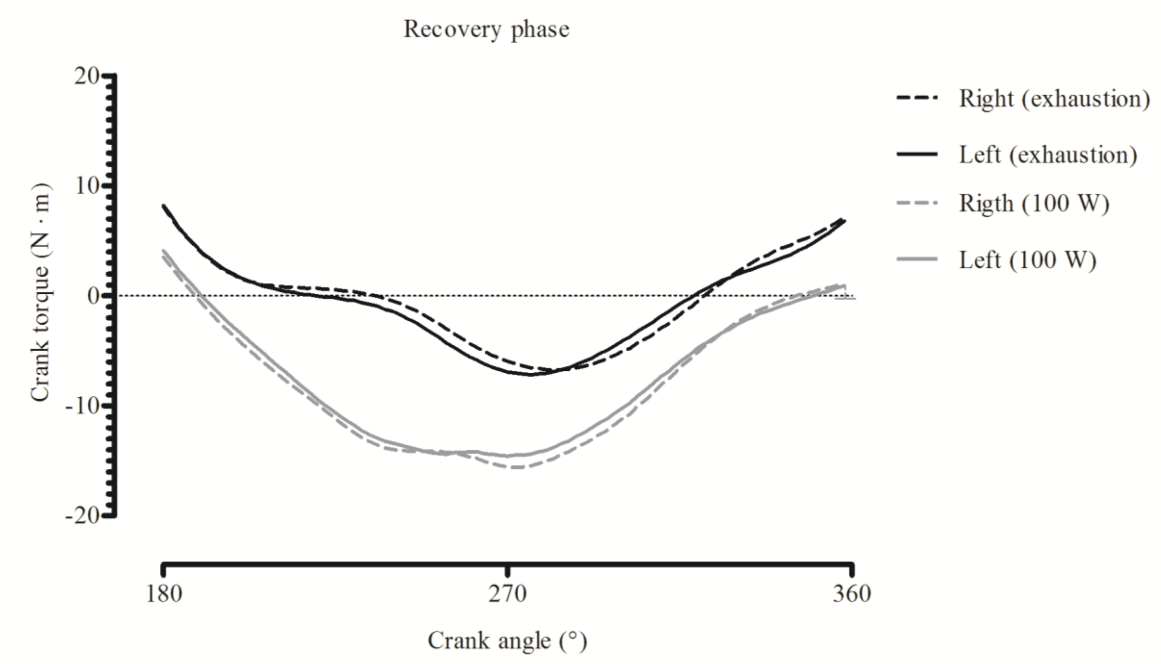
Further studies are required to investigate bilateral symmetry in thermal, kinetic and kinematics variables throughout submaximal incremental efforts.

Conclusions

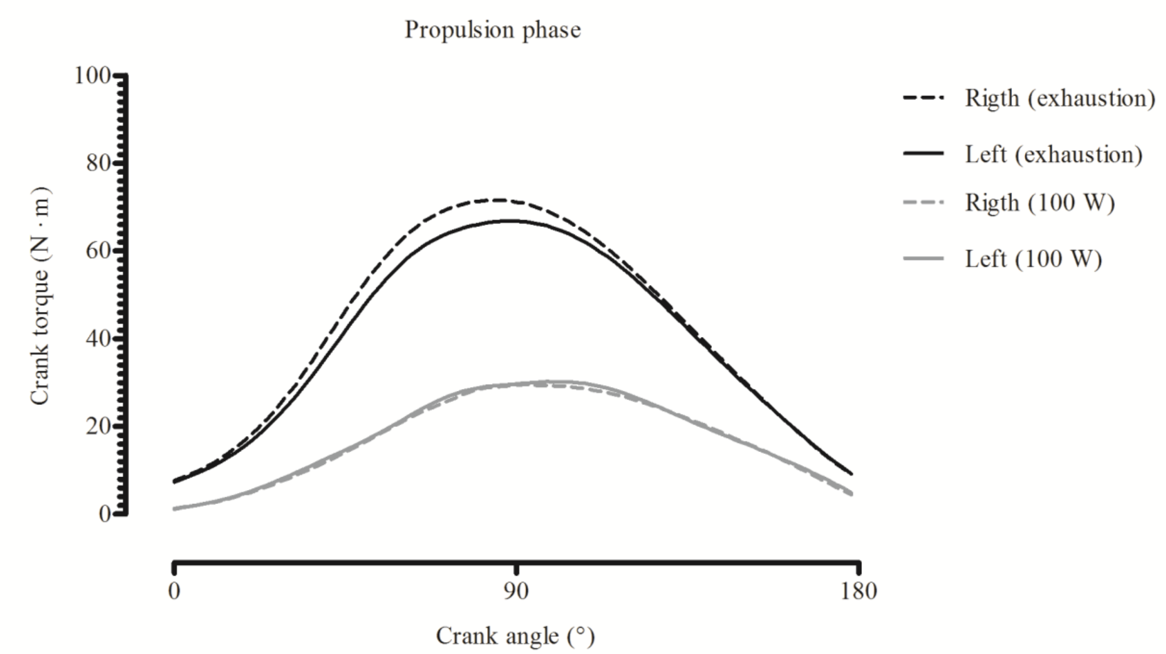
Elite competitive cyclists showed bilateral asymmetry between propulsive peak crank torques in a state of extreme fatigue (i.e. at the exhaustion). Skin temperature dynamics measured by IRT presented similar behaviour in both right and left limb highlighting a certain thermal asymmetry in response to maximal incremental test.

APPENDICES

Appendix 1. Right and left crank torques evolution of a cyclist during the recovery phase



Appendix 2. Right and left crank torques evolution of a cyclist during the propulsion phase



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