

University of Groningen

Staying on track

Stoter, Inge

DOI:
[10.33612/diss.113131465](https://doi.org/10.33612/diss.113131465)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2020

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):
Stoter, I. (2020). *Staying on track: the road to elite performance in 1500m speed skating*. [Thesis fully internal (DIV), University of Groningen]. <https://doi.org/10.33612/diss.113131465>

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Underlying performance characteristics

Pacing strategy, muscle fatigue and technique in 1500m speed skating and cycling time-trials.

Chapter 3



Adapted from:

Stoter, I. K., MacIntosh, B. R., Fletcher, J. R., Pootz, S., Zijdewind, I., & Hettinga, F. J. (2016). Pacing Strategy, Muscle Fatigue and Technique in 1500m Speed Skating and Cycling Time-Trials. *International journal of sports physiology and performance*, 11(3), 337-343.

Abstract

Purpose: To evaluate pacing behavior and peripheral and central contributions to muscle fatigue in 1500-m speed-skating and cycling time trials when a faster or slower start is instructed. **Methods:** Nine speed skaters and 9 cyclists, all competing at regional or national level, performed two 1500-m time trials in their sport. Athletes were instructed to start faster than usual in 1 trial and slower in the other. Mean velocity was measured per 100 m. Blood lactate concentrations were measured. Maximal voluntary contraction (MVC), voluntary activation (VA), and potentiated twitch (PT) of the quadriceps muscles were measured to estimate central and peripheral contributions to muscle fatigue. In speed skating, knee, hip, and trunk angles were measured to evaluate technique. **Results:** Cyclists showed a more explosive start than speed skaters in the fast-start time trial (cyclists performed first 300 m in 24.70 ± 1.73 s, speed skaters in 26.18 ± 0.79 s). Both trials resulted in reduced MVC ($12.0\% \pm 14.5\%$), VA ($2.4\% \pm 5.0\%$), and PT ($25.4\% \pm 15.2\%$). Blood lactate concentrations after the time trial and the decrease in PT were greater in the fast-start than in the slow-start trial. Speed skaters showed higher trunk angles in the fast-start than in the slow-start trial, while knee angles remained similar. **Conclusions:** Despite similar instructions, behavioral adaptations in pacing differed between the 2 sports, resulting in equal central and peripheral contributions to muscle fatigue in both sports. This provides evidence for the importance of neurophysiological aspects in the regulation of pacing. It also stresses the notion that optimal pacing needs to be studied sport specifically, and coaches should be aware of this.

Keywords

Athletic performance, central fatigue, peripheral fatigue and sport science

Introduction

Long-track speed skating is an intriguing sport to study: The crouched position in combination with the static gliding phase, a sideward push-off (de Koning, Thomas, Berger, de Groot, & van Ingen Schenau, 1995; de Koning, Foster, Lampen, Hettinga, & Bobbert, 2005; Hettinga et al., 2011; van Ingen Schenau, 1982), and high velocities requires high quasi-isometric muscle forces. The crouched position is important for aerodynamics and technique, as smaller knee angles diminish air resistance (van Ingen Schenau, 1982), and is essential to increase push-off length, enabling a more effective technique (van Ingen Schenau & Bakker, 1980). Often when speed skaters fatigue, they increase their body angles (de Koning et al., 2005), probably to reduce blood-flow restrictions associated with the crouched position (Foster et al., 1999). The trade-off between positive and negative aspects of changing body angles in relation to muscle fatigue affects the ability of speed skaters to benefit from a fast start during a 1500-m time trial. Modeling studies that included both physiological (such as anaerobic and aerobic energy contribution) and biomechanical parameters (such as frictional energy losses) have calculated that a faster start should improve 1500-m speed-skating and cycling performance (de Koning et al., 2005; Hettinga et al., 2011; Hettinga, de Koning, Hulleman, & Foster, 2012; van Ingen Schenau, de Koning, & de Groot, 1990). Nevertheless, imposing a faster start in 1500-m speed skating resulted in slower end times, presumably due to its impact on postural control and increasing body angles, supposedly associated with earlier onset of muscle fatigue (Hettinga et al., 2011; Hettinga et al., 2012). Until now, muscle fatigue has never been quantified and analyzed in speed skating. Muscle fatigue is often defined as an exercise-induced reduction in the force-generating capacity of the neuromuscular system (Bigland-Ritchie, Johansson, Lippold, & Woods, 1983) and is generally measured by changes in maximal voluntary contraction (MVC). Both central (at or proximal to the motor neuron) and peripheral (distal from the motor neuron) mechanisms play an important regulatory role in muscle fatigue (Gandevia, 2001) and in pacing (Roelands, de Koning, Foster, Hettinga, & Meeusen, 2013). Central fatigue reflects impaired voluntary drive, whereas peripheral mechanisms are more related to changes in excitation-contraction coupling in the muscle fibers (D. G. Allen, Lamb, & Westerblad, 2008; Gandevia, 2001).

It is still unclear, however, to what extent muscle fatigue and technique affect pacing and performance. Speed skating and cycling share similar characteristics such as the cyclic movement, crouched position, active muscles, and maximal velocity (Herzog, Guimaraes, Anton, & Carter-Erdman, 1991; Hettinga et al., 2011; Hettinga et al., 2012; van Ingen Schenau, de Koning, & de Groot, 1994). The increasing body angles, however, do not occur in cycling, as the body is supported by the bicycle, leaving only positive aspects of the crouched body position. The current study assessed muscle fatigue, pacing, and technical parameters in a competitive setting. Essential to this is that subjects perform in a competitive setting, receiving pacing instructions instead of rigidly imposed

pacing strategies. In this way, we included the behavioral component of pacing: Although they are guided by our instructions, the athletes decide when and how much to accelerate or decelerate (Renfree, Martin, Micklewright, & St Clair Gibson, 2014; Smits, Pepping, & Hettinga, 2014). This approach will provide new valuable insights to performance of athletes in competitive settings that cannot be obtained in a laboratory design. Well-controlled laboratory studies are valuable in resolving underlying regulatory mechanisms but need accompanying ecologically valid field studies in which the essential pillars of sport-science psychology, physiology, and biomechanics are combined (Konings et al., 2015).

To evaluate the role of muscle fatigue in the earlier observed differences in pacing between speed skating and cycling in a realistic competitive setting, we evaluated the contribution of peripheral and central fatigue in speed-skating and cycling time trials. We hypothesized that cyclists would perform a faster initial phase of the time-trial than speed skaters but that the impact of pacing strategy on muscle fatigue would be the same. This would provide evidence that different behavioral adaptations depending on the nature of the sport result in similar neurophysiological limitations.

Methods

Subjects

Nine well-trained male speed skaters (age 21 ± 3 y, height 182 ± 6 cm, weight 75 ± 6 kg) and 9 well-trained male cyclists (age 25 ± 9 y, height 184 ± 7 cm, weight 78 ± 4 kg) participated and gave written informed consent. All subjects were competing at regional or national level, training at least 3 times per week. The study protocol was approved by the institutional review board, in the spirit of the Helsinki Declaration.

Protocol

Subjects performed two 1500-m time trials in their sport of expertise. To create significantly different pacing strategies, athletes were instructed to start (first 300 m) 0.5 second faster than their customary pacing strategy in the 1 trial (fast start: FS) and 0.5 second slower in the other (slow start: SS). That 0.5 second is beyond the variation of 0.1 second that was seen when speed skaters were instructed to go all out compared with self-paced performance (Hettinga et al., 2011) but within the range of intraindividual differences seen in official time trials during 1 season. The remaining 1200 m had to be finished as fast as possible. Each subject performed the trials in random order at the same time of day, with 1 week between trials in a period with no important competitions. Subjects were requested to keep training intensity low the day before testing, refrain from caffeine for 12 hours before testing, and to not eat in the 2 hours preceding testing.

Speed skaters performed their 1500-m trials at an indoor 400-m speed-skating track in Calgary, AB, Canada, 1035 m above sea level ($n = 3$), or in Groningen, the Netherlands, 5 m above sea level ($n = 6$). To increase sample size, data were pooled. The start was situated in the outer competition lane. Subjects were not aware of split times during the trial.

Cycling trials were performed in Calgary on the Velotron Dynafit-Proergometer (RacerMate Inc, Seattle, WA, USA) simulating outdoor-track performance, including wind resistance. The accuracy of the Velotron is 3.0% (CI = 1.6–4.5%) during high-intensity intervals and <1% during constant-power trials.¹⁸ A familiarization trial was performed 1 week before the first trial. Subjects only received distance feedback.

Before and after each time trial, blood lactate concentration (BLC) and muscle force were measured. During the time trial, pacing strategy (velocity profiles) and technique (body angles) were measured.

Pretrial

Barometric pressure, ice temperature, humidity, and indoor temperature were measured before every speed-skating trial. For cycling, barometric pressure and indoor temperature were constant between 880 and 891 hPa and 19°C and 21°C, respectively.

The Lactate Pro (LP, Arkray KDK, Japan) was used to measure baseline fingertip BLC at rest,^{19,20} followed by baseline muscle-force measurements performed on a customized chair with attached force sensor, which was calibrated before each trial. The subject was seated upright, strapped with a seatbelt across his waist and ankle attached to the force sensor at a 90° knee angle. Force measurements were done on the left leg in Calgary but on the right leg in Groningen. Force measurements were repeated 3 times (Groningen) or 2 times (Calgary), with 1 minute rest between repetitions. Force output (N) was recorded by Windaq (Calgary) or Spike2 (Groningen) software with a frequency of 3000 Hz or 500 Hz, respectively.

MVC, voluntary activation (VA), and potentiated twitch (PT) were obtained to quantify muscle performance. A decline in MVC (baseline vs post) indicates muscle fatigue as a result of both peripheral and central fatigue. Peripheral fatigue was quantified by changes (baseline vs post) in PT, and central fatigue by changes in the VA (Gandevia, 2001; Shield & Zhou, 2004).

To determine MVC, maximal force was measured during a 5-second maximal isometric contraction of the quadriceps femoris, with verbal encouragement. To assess VA and PT, electrical stimulation was applied to the femoral nerve to activate the quadriceps during and 5 seconds after the MVC. Two stimulation pads were placed on the leg and connected to a high-voltage stimulator (Digitimer DS7A[H] or 3 parallel DS7A-models). The cathode pad was placed at the

distal side of the middle of the inguinal crease. The anode pad was placed 2 to 3 cm proximal to the patella, with the knee in a bent position. Before each trial the current that evoked maximal twitch amplitude at rest was determined with stepwise current increases (minimum step: 25 mA) until twitch amplitude did not increase. The current evoking the maximal twitch amplitude was used throughout the experiment.

VA was quantified by use of the equation $VA(\%) = (1 - IT/PT) \times 100$, where IT = interpolated twitch (G. M. Allen, Gandevia, & McKenzie, 1995; G. M. Allen, McKenzie, & Gandevia, 1998). The underlying principle is that an imposed electrical stimulation delivered to the motor nerve of muscles that perform an MVC will evoke an increase in muscle activation when the voluntary activation is submaximal (MERTON, 1954; Shield & Zhou, 2004). The force evoked by the imposed electrical stimulation on top of the MVC is the IT, and the force evoked by the electrical stimulation 5 seconds after MVC is PT.

After baseline measurements, athletes performed a 10-minute low-intensity warm-up including 2 brief accelerations. Cyclists warmed up on the bicycle, whereas speed skaters had a 5-minute off-ice warm-up followed by a 5-minute on-ice warm-up.

Time trial

Mean velocities per 100 m were obtained during all time trials. For cycling this was obtained by the ergometer. For speed skating, infrared timing gates (TC timing system, Brower, USA, in Calgary; HL 2-31 Photocell, TAG Heuer professional timing, Switzerland in Groningen) were placed at the entry and exit of every corner to measure split times for every straight and curve.

Changes in speed-skating technique were determined by changes in knee, hip, and trunk angles (Figure 1) measured at every straight. One high-resolution camera, located in the middle of the 400-m track, filmed the speed skater in the sagittal plane. Body angles were taken over 5 frames with the left leg in gliding phase and the right leg in recovery phase with close to 90° knee angle (Figure 1) and corrected for viewing angle.

Posttrial

Within 2 to 4 minutes after completion of the time trial, force measurements were repeated. The percentage decrease of the posttrial measurement relative to baseline was used to quantify the amount of muscle fatigue present after the trial. In addition, BLC was measured 7 times at intervals of 5 minutes starting 5 minutes after the subject had finished his time trial. BLC_{post} , including all 7 BLC measurements after the time trial, and BLC_{max} , being the highest posttrial BLC value, were obtained. All subjects performed a 10-minute active cycling recovery, starting 20 minutes after time-trial completion.

Statistics

The highest VA and PT and mean MVC of the baseline and post-trial force measurements were used for analysis. Velocity and body angles were analyzed per lap for 0 to 300 m, 300 to 700 m, 700 to 1100 m, and 1100 to 1500 m, as is common in speed skating. Pearson correlation coefficients were calculated to determine the relationship of BLC_{max} with VA, PT, and MVC. Further statistical analysis was done with mixed analysis of variance (ANOVA), with strategy (FS vs SS) as within-subject variable and sport (cycling vs speed skating) or location (Calgary vs Groningen) as a between-subjects variable. For statistical analysis of mean velocity per lap, BLC_{post} , and force measurements, the within-subject variable lap or time (before vs after or time after trial) was added to the mixed ANOVA. Body angles were tested in speed skating only, with a 2-way repeated-measures ANOVA with strategy and lap as within-subject variables. When the assumption of sphericity was violated, degrees of freedom were corrected (Greenhouse-Geisser). When a 3-way interaction effect was found, a post hoc analysis was performed with a 2-way repeated-measures ANOVA. Planned contrasts (repeated; T_1-T_2 , T_2-T_3 , etc) were used on the main and 2-way interaction effects involving lap or time.



Figure 1. Trunk angle (θ_1), hip angle (θ_2), and knee angle (θ_3).

Results

External conditions

In speed skating no interaction effects of strategy \times location or main effect for trial were found for ice temperature, indoor temperature, and barometric pressure. There were main effects for location for ice temperature ($F_{1,7} = 36.489$; $P = .001$), indoor temperature ($F_{1,7} = 261.241$; $P < .001$), and barometric pressure ($F_{1,7} = 1368.7$; $P < .001$), showing lower mean ice temperatures ($-6.9^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$; $-5.6^{\circ}\text{C} \pm 0.9^{\circ}\text{C}$), higher indoor temperatures ($15.1^{\circ}\text{C} \pm 0.7^{\circ}\text{C}$; $4.1^{\circ}\text{C} \pm 3.9^{\circ}\text{C}$), and lower barometric pressures (884 ± 6 hPa; 1022 ± 12 hPa) in Calgary than in Groningen. These differences were deemed inconsequential since athletes performed both time trials in the same location.

Start and end times

Start times at 0 to 300 m and 1500-m end times are presented (Table 1). For start times, an interaction effect of strategy \times sport ($F_{1,16} = 5.276$; $P = .035$) was found, with similar start times in SS for both sports but relatively faster start times in FS for cyclists than for speed skaters.

Table 1. 0- to 300-m split time and 0- to 1500-m end times for the fast-start and slow-start trials in speed skating and cycling, mean (SD)

	Speed-Skating Time (s), n=9		Cycling Time (s), n=9	
	Fast start	Slow start	Fast start	Slow start
0–300 m ^a	26.18 (0.79)	27.27 (0.79)	24.70 (1.73)	27.41 (3.00)
0–1500 m	129.5 (4.1)	130.4 (3.5)	127.5 (6.9)	127.6 (7.0)

^a Strategy \times sport interaction effect.

For end times, neither a strategy \times sport interaction effect ($P = .46$) nor main effects of sport ($P = .37$) and strategy ($P = .28$) were found, revealing no differences in end times for sports or trials.

Velocity

Mean velocities per lap are presented in Table 2. To provide more insight into the variation during the time trial, velocity profiles for FS and SS are also presented per 100 m for speed skating and cycling in Figure 2.

An interaction effect of strategy \times lap \times sport ($F_{2,019,32,304} = 7.126$; $P = .003$) was found. Post hoc analysis yielded interaction effects of strategy \times lap for speed skating ($F_{1,434,11,476} = 11.118$; $P = .004$) and cycling ($F_{1,733,13,862} = 20.392$; $P < .001$), suggesting different pacing strategies for FS

Table 2. Mean velocities (km/h) per lap for the fast-start and slow-start trials in speed skating and cycling, mean (SD)

	SpeedSkating, n=9		Cycling, n=9 ^a	
	Fast start	Slow start ^b	Fast start	Slow start ^b
0–300 m	42.31 (1.18)	40.56 (1.23)	45.68 (3.30)	41.48 (4.80)
300–700 m	45.30 (1.41)	44.60 (1.52)	45.65 (2.64)	46.26 (2.74)
700–1100 m	41.51 (1.75)	41.94 (1.60)	41.25 (2.26)	42.73 (3.19)
1100–1500 m	39.34 (1.74)	39.59 (1.25)	40.20 (2.68)	41.27 (2.93)

a Strategy × lap × sport interaction effect. b Strategy × lap interaction effect.

Pacing strategies

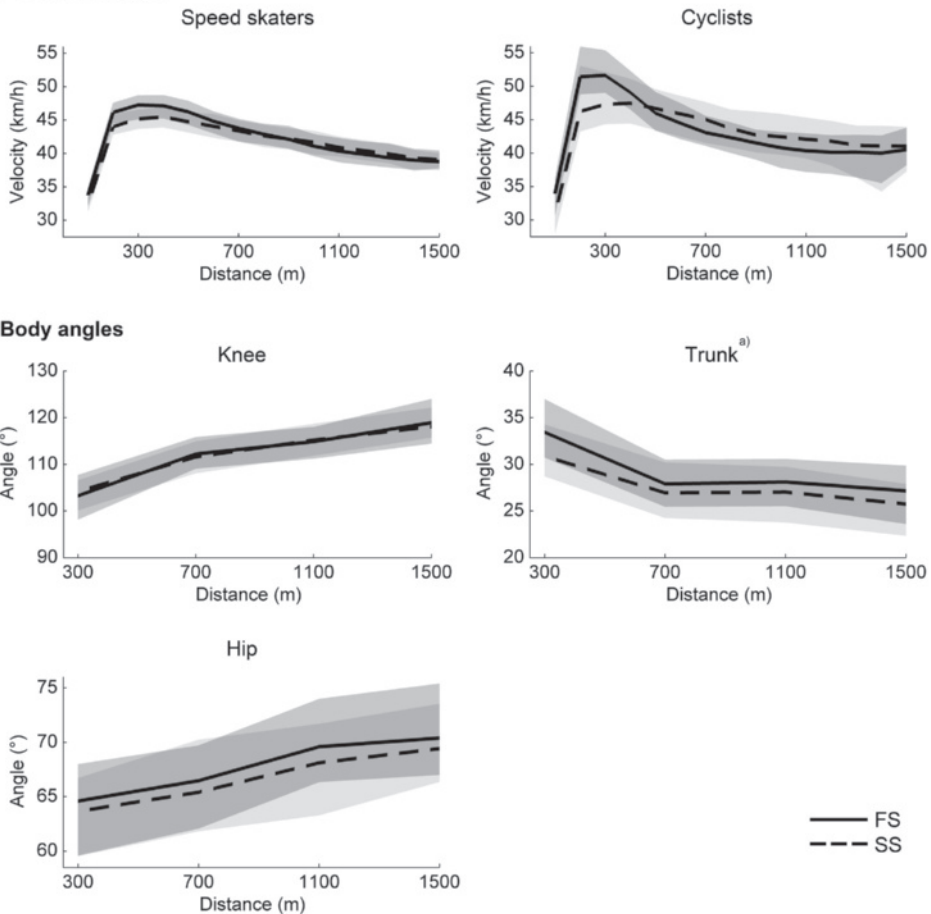


Figure 2. Velocity (pacing) profiles for the fast-start (FS) and slow-start (SS) 1500-m time trials in speed skating (n = 9) and cycling (n = 9) and body angles for speed skating (n = 8)—knee, trunk, and hip angles per lap. Solid (FS) and dashed (SS) lines represent mean velocity, and shades represent ± SD. ^{a)} A main effect for strategy ($P < .05$).

and SS in both sports. In speed skating, the planned contrasts showed a different strategy \times lap interaction for laps 1 to 2 and 2 to 3, showing a relatively faster start in FS than in SS and a greater decrease in mean velocity from lap 2 to 3 in FS than in SS. Planned contrasts in cycling showed a different strategy \times lap interaction from lap 1 to 2, indicating a relatively faster first lap in FS than in SS.

Force measurements

Results of force measurement at baseline and posttrial, as well as the percentage decrease (posttrial relative to baseline), in force measurements are presented in Table 3.

No strategy \times time (baseline vs post) \times sport interactions were found for MVC ($P = .91$), VA ($P = .24$), and PT ($P = .46$). In addition, no interaction effects were found for MVC ($P = .37$; $P = .65$; $P = .19$), VA ($P = .50$; $P = .32$; $P = .80$), and PT ($P = .14$; $P = .56$; $P = .07$) for strategy \times sport, time \times sport, or strategy \times time.

Main effects of sport were found for MVC ($F_{1,16} = 6.186$; $P = .024$) and PT ($F_{1,16} = 6.044$; $P = .026$), indicating higher average values in speed skating than in cycling. No main effect was found for VA ($P = .70$).

Main effects of strategy were only found for MVC ($F_{1,16} = 6.940$; $P = .018$), indicating higher MVC values in SS than in FS. No main effects for strategy were found for VA ($P = .39$) or PT ($P = .16$). Main effects of time were found for MVC ($F_{1,16} = 20.256$; $P < .001$), VA ($F_{1,16} = 5.708$; $P = .030$), and PT ($F_{1,16} = 40.364$; $P < .001$). Lower measurements were found posttrial than at baseline, indicating the occurrence of general muscle fatigue (MVC), with both central (VA) and peripheral (PT) fatigue contributing.

Percentage decrease in force measurements

The percentage decrease in force did not result in a strategy \times sport interaction effect or a main effect for sport for MVC ($P = .62$; $P = .26$, respectively), VA ($P = .24$; $P = .32$, respectively), or PT ($P = .06$; $P = .32$, respectively).

A main effect of strategy was found for the decrease in PT ($F_{1,16} = 4.981$; $P = .04$), showing a greater percentage decrease in FS ($29.2 \pm 14.9\%$) than in SS ($21.7\% \pm 15.0\%$), indicating a stronger contribution of peripheral fatigue to muscle fatigue in FS than in SS. No main effects of strategy were found for the decrease in either MVC ($P = .26$) or VA ($P = .32$).

Blood lactate concentration

Baseline BLC and BLC_{post} are presented in Figure 3. Baseline BLCs yielded no strategy \times sport interaction ($P = .29$) and no main effect for sport ($P = .36$) or strategy ($P = .11$). For BLC_{post}, 5 to 35 minutes after the trials, no 3-way ($P = .728$) or 2-way interaction effects or main effect for sport ($P = .06$) were found. Main effects for strategy ($F_{1,16} = 6.112$; $P = .025$) and time ($F_{6,96} = 194.977$; $P < .001$) were found, indicating higher BLC_{post} values after FS than after SS and decreases in BLC_{post} starting 10 minutes after finishing the trial across both sports.

Table 3. Maximal voluntary contraction, voluntary activation, and potentiated rest twitch of speed skaters and cyclists before (baseline) and after the fast-start (FS) and slow-start (SS) trials, mean (SD)

		Both Trials				
		Baseline	Posttrial	Decrease (%)	FS decrease (%)	SS decrease (%)
Maximal voluntary contraction (N)	Speed skaters	642 (196)	581 (174)	8.6 (12.3)	9.8 (15.9)	7.4 (8.1)
	Cyclists	488 (81)	413 (101)	15.5 (16.1)	18.4 (15.3)	12.4 (17.2)
	All subjects	565 (167)	497 (164) ^a	12.0 (14.5)	14.1 (15.8)	9.9 (13.3)
Voluntary activation (%)	Speed skaters	86.9 (10.3)	85.5 (10.7)	1.4 (4.9)	0.4 (4.9)	2.3 (5.0)
	Cyclists	89.5 (7.3)	86.1 (9.3)	3.4 (4.9)	4.0 (6.2)	2.8 (3.5)
	All subjects	88.2 (8.9)	85.8 (9.9) ^a	2.4 (5.0)	2.2 (5.7)	2.6 (4.2)
Potentiated rest twitch (N)	Speed skaters	249 (65)	164 (52)	24.8 (13.9)	25.1 (14.2)	24.4 (14.5)
	Cyclists	199 (39)	134 (47)	26.1 (16.8)	33.3 (15.2)	18.9 (16.0)
	All subjects	224 (58)	149 (51) ^a	25.4 (15.2)	29.2 (14.8)	21.7 (15.0) ^b

^a Main effect for time. ^b Main effect for strategy.

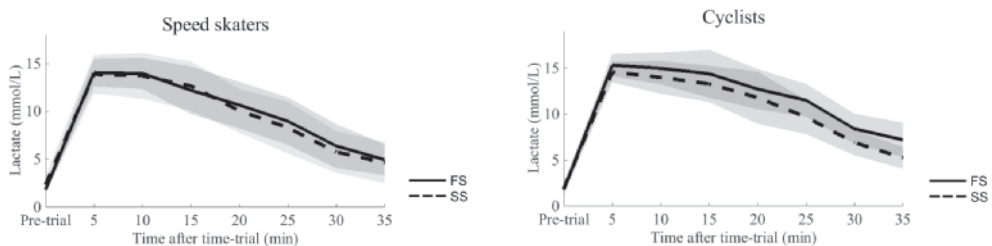


Figure 3. Blood lactate concentrations for the fast-start (FS) and slow-start (SS) trials in speed skating and cycling.

Speed skaters had a BLC_{max} of 14.5 ± 1.7 mmol/L in FS and ± 1.4 mmol/L in SS. Cyclists had a BLC_{max} of 16.3 ± 1.8 mmol/L in FS and 15.1 ± 1.8 mmol/L in SS. For BLC_{max} , no strategy \times sport interaction ($P = .07$) was found and no main effects for strategy ($P = .33$) or sport ($P = .14$).

BLC_{max} was significantly correlated with percentage decrease in MVC ($r = .518$, $P = .025$) and percentage decrease in PT ($r = .556$, $P < .001$) but not with percentage decrease in VA ($r = .315$, $P = .062$).

Body angles

For the speed skaters, body angles are presented in Figure 2. Unfortunately, 1 subject did not have a full data set for the body angles. No strategy \times lap interaction effects were found for knee ($P = .13$), hip ($P = .93$), and trunk angles ($P = .39$). Main effects for lap were found for knee ($F_{3,21} = 86.486$; $P < .001$), hip ($F_{3,21} = 16.176$, $P < .001$), and trunk angles ($F_{3,21} = 24.181$; $P < .001$). Contrasts showed increasing knee angles in all laps, increasing hip angles in all laps except for laps 3 to 4, and decreasing trunk angles from lap 1 to 2 (Figure 2). In addition, a main effect for strategy was found for trunk angles ($F_{1,7} = 12.280$; $P = .010$), with higher trunk angles in FS than in SS. No main effect of strategy was found for knee ($P = .74$) or hip angles ($P = .27$).

Discussion

The current study is the first to report data on muscle fatigue in speed skating. It was shown that both peripheral and central mechanisms contribute to muscle fatigue in 1500-m speed skating, as well as in cycling time trials. However, consistent with previous reports investigating cycling and speed skating separately (Hettinga et al., 2011; Hettinga et al., 2012), the current study showed a relatively more explosive start in FS for cyclists than for speed skaters. We can thus conclude that, as hypothesized, cyclists and skaters adapted different behavioral approaches to pacing while receiving equal instructions and while contributions of muscle fatigue did not differ between sports. This provides evidence for the importance of neurophysiological aspects involved in regulatory mechanisms responsible for pacing, as suggested in a recent literature review (Roelands et al., 2013). Speed skaters were not willing to sacrifice their crouched position and chose a less explosive strategy, while knee angles followed the same profile throughout FS, as well as SS. FS resulted in slightly higher trunk angles than in SS. Possibly, speed skaters started less explosively to maintain speed at the end of the race, consistent with the proposal that maintaining body posture and coordination is more important in speed skating than in cycling. This was further supported by the greater loss of skating velocity in laps 2 to 3 in FS than in SS, while mean velocity over the last 2 laps did not differ.

The current design uniquely combines neurophysiological and biomechanical measures in a realistic competitive setting as advised in a recent literature review on speed skating (Konings et al., 2015) while leaving room for the behavioral pacing responses of the athletes to the given instructions as an outcome measure. We do realize that our choice to study behavior in a setting that is as close to competitive performance as possible consequently led to some limitations of the study, as well. We chose to use 2 different groups of athletes (cyclists and speed skaters) and have them all perform in their sport of expertise. Although this is very realistic, it does prevent a repeated-measures design with sport as a within factor. To increase our limited subject number, a common problem in sport science, we pooled measurements at different locations. As temperature has been shown to affect processes associated with muscle fatigue and pacing (Roelands et al., 2013), differences need to be noted here: The 6 Groningen skaters performed the time trial at lower temperatures than the cyclists and 3 Calgary skaters, which might explain the relatively high variability in the muscle-fatigue measurements. In addition, skaters were tested on different legs, while asymmetry has been shown in speed skating (Hesford, Laing, Cardinale, & Cooper, 2012). However, muscle-fatigue measurements were all performed off ice, in a room-temperature environment, and on the same leg before and after exercise. We believe that these limitations are important to note, but at the same time, they have limited impact. The study provides interesting and novel outcomes on behavioral pacing adaptations in relation to neurophysiological measures in a realistic sport setting.

A mean BLC_{max} of 14 to 16 mmol/L in all time trials indicated that they were performed with maximal effort (Gass, Rogers, & Mitchell, 1981), and the decrease in MVC indeed confirmed the presence of muscle fatigue. The current paper also demonstrated that both peripheral and central mechanisms contributed to muscle fatigue in all time trials. Nevertheless, the decreases in VA (central fatigue (Gandevia, 2001)) were relatively small compared with decreases in MVC and PT (Table 3). For all force-related variables, the 4-minute delay between end of trial and the force measurements should be kept in mind. As some recovery is likely, muscle-fatigue mechanisms could thus not be estimated to their full extent (Fernandez-del-Olmo et al., 2013; Sidhu, Bentley, & Carroll, 2009). Speculation about the recovery from central and peripheral fatigue is difficult, as recovery of muscle fatigue is task dependent and no data comparing cycling and speed skating are available. We did establish that, conforming with previous literature (Sidhu et al., 2009), greater (peripheral) fatigue was associated with greater metabolic demand, as confirmed by the association between BLC and PT and muscle fatigue. Differences between trials were found in posttrial BLC and PT. BLC_{post} was higher after FS than after SS, and peripheral fatigue (PT) was more evident after FS. FS thus seemed to cause somewhat more homeostatic disturbance and peripheral fatigue than SS. Future studies aimed at understanding fatigue, pacing, and recovery in different sports are recommended.

Practical applications

The current study provides evidence that both peripheral and central contributions of muscle fatigue are involved in the regulatory process of pacing. It seems that athletes of different sports adapt their strategy differently when responding to similar instructions, resulting in a similar level of muscle fatigue. This stresses the notion that optimal pacing needs to be studied sport specifically, and coaches should be aware of this. It is advised to further explore muscle fatigue, pacing, and technique under controlled and standardized laboratory settings to place alongside these unique field data.

Conclusion

Both peripheral and central mechanisms contributed to muscle fatigue in 1500-m speed skating, as well as in cycling. While contributions of muscle fatigue were not different between sports, behavioral pacing adaptations differed, with a more explosive start for cyclists than for speed skaters. Speed skaters presumably anticipated muscle fatigue, homeostatic disturbance, and the subsequent deleterious effect on their technique and adapted their behavior to the nature of the sport to complete the time trial with neurophysiological limitations similar to those in cycling. This provides evidence for the importance of neurophysiological aspects involved in regulatory mechanisms responsible for pacing.

Acknowledgments

The authors would like to thank all subjects who took part in the research and, in particular, Prof Bert Otten; Shane Esau, MKin; and Faes Kerkhof, MSc, for their help during the project. Also we would like to thank Sports Center Kardinge, Groningen, the Netherlands, and the Olympic Oval, Calgary, AB, Canada, for their hospitality providing us the opportunity to perform our measurements. There were no funding sources for the current article and there are no conflicts of interest for any author on this article. Finally, the results of the current study do not constitute endorsement of the product by the authors or the journal.

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1500m



Pacing