Influences of Compression Cycling Skinsuit on Energy Consumption of Amateur Male Cyclists

Abstract

Energy consumption differences of two cycling garments during short-term cycling were studied. Eleven amateur male cyclists participated in two cycling sessions over two days while wearing a newly designed compression cycling skinsuit (CCS) with stripes simulating kinesio-tape, and a conventional compression garment (CG) (control garment). In each session, the participants performed a twelve sets of short-term cycling combination of three workloads and four cadences with either CCS or CG. Each combination lasted for 30 seconds. Garment pressure values at the thigh, oxygen consumption (VO_2) and heart rate (HR) were collected and analysed. CCS provided significantly different pressure values ($P < 0.05$) at two front muscles (i.e., rectus femoris (RF), vastus lateralis (VL) and one back muscle (i.e., biceps femoris (BF)) during all three workloads, and at a front middle muscle (i.e., vastus medialis (VM)) only during low workload cycling. There was a statistically significant interaction between garment and workload ($P < 0.05$) on VO_2 when cycled at 120 rpm. CCS required low VO_2 ($P < 0.05$) when the cycling combination of workload and cadence are reversed in its trend either low workload and high cadence or high workload and low cadence cycling. Simultaneously, CCS had a significant impact on HR during high workload cycling ($P < 0.05$). In conclusion, CCS's higher compression power at thigh muscles was found to be effective in energy consumption reduction during short-term cycling with low and high workload.

Keywords: Pressure; physiological effect; oxygen consumption; heart rate

Introduction

Since their introduction to competitive sports in the 1990s,[1] compression garments (CG) became popular due to their positive effects associated with performance enhancement and quick fatigue recovery. The principle behind the positive effects of CG was that its gradual pressure improved venous return by artificially increasing the extravascular pressure difference closer to a resting stage,[2-4] which accelerates metabolite clearance, oxygenation and vascular load reduction.[5] This positive hemodynamic benefited athletes' performance and recovery.[3,6] Hemodynamic changes simultaneously affected the physiological responses during physical activities especially on oxygen consumption (VO_2) and heart rate (HR). HR was decreased when venous return was improved by CG during intense exercise,[3] and linearly related to energy expenditure and VO_2 during dynamic activities involving large muscles.[7-9] The more oxygen an athlete consumed during high-intensity exercise, the more the body generated adenosine triphosphate (ATP) energy in cells. ATP is referred to as the 'molecular unit of currency' of intracellular energy, and VO_2 is an essential measure of the body's ability to generate ATP which is the energy source for muscles during high-intensity exercise. When the exercise becomes intense, the breathing becomes faster and deeper to supply more oxygen to working muscles in order to generate enough ATP to keep moving.[10] Thus, decreased VO_2 and HR during exercise indicates less energy consumption and more efficient performance in subsequent exercise bouts.[11]

Research gap

However, previous studies concerning CG's impact on the sports performance were contradicting. Some studies found that CG had a significant influence on cycling performance where compression exerted by CG could decrease the rate of fatigue by improving the physiological responses (e.g., HR),[2,3,5,6,12] while some found no significant influence on cycling performance,[4,13-15] VO_2 or HR during cycling.[2,4,6,12-15] Thus, a further investigation on CG's impact on physiological response during cycling was needed.

The previous studies predominantly used the lower body CG including tights, compression stockings, and compression calf sleeves while the impact of the knee-length one-piece skinsuit was not investigated despite its aerodynamic advantages (e.g., energy saving) made it popular for professional cycling competition.[16,17]

Recently, the CG with kinesio-tape concept became popular. Kinesio-tape, a therapeutic equipment, has been widely used by the athletes for performance enhancement and fatigue recovery since 1981.[18] Kinesio-tape facilitated muscle elasticity and strength during sports with its soft tissue manipulation, fascia and muscle relaxation, ligament and tendon support, movement rectification and lymphatic fluid circulation.[11] It not only strengthened the physical power but also significantly changed the participants' perception on exertion level during sports.[19] An application of adhesive silicone stripes on CG improved performance during jogging by reducing the energy consumption.[20] A direct application of kinesio-tape on CG pants in the same manner as onto the skin improved performance significantly during jumping and isokinetic exercise.[21] Although kinesio-tape's positive impact on sports performance brought several CG with stripes simulating kinesio-tape on to the market, its effect on cycling had not been clearly understood.

Research purpose

Therefore, the aim of this study was to investigate the influences of compression cycling skinsuit (CCS) with stripes simulating kinesio-tape on the VO_2 and HR and subsequent energy consumption during cycling. It was hypothesized that CCS with stripes simulating kinesio-tape would enhance the cycling performance while saving energy during cycling in comparison with the CG. The effect of newly designed cycling skinsuit with stripes simulating kinesio-tape on both physiological responses and pressure changes during cycling at different workload and cadence was investigated.

Method

The pressure values of the thigh, VO_2 and HR were collected and analysed by two experiment sessions when either CCS or CG was worn with randomized order, while each session included a twelve sets of short-term cycling combination of three workloads and four cadences. The intra-class correlation coefficient and the standard error of measurement were calculated to further determine the reliabilities of HR and VO_2, and pressure at each condition.

Hypothesis design

A total of three hypotheses were formulated on the basis of previous studies concerning clothing-induced energy consumption differences during cycling.

H1: CCS would provide higher pressure values to the thigh muscles during static standing and dynamic cycling than CG.

H2: CCS would improve physiological responses (i.e., lower VO_2 and HR) compared to CG during all cycling combinations.

H3: CCS would promote less energy consumption than CG during all cycling combinations.

In these three hypotheses, it was assumed that pressure values of thigh muscle groups would be higher when wearing CCS during both static standing and dynamic cycling, while the energy consumption would be quantified by physiological measurements (i.e., VO_2 and HR) when wearing CCS during all cycling combinations.

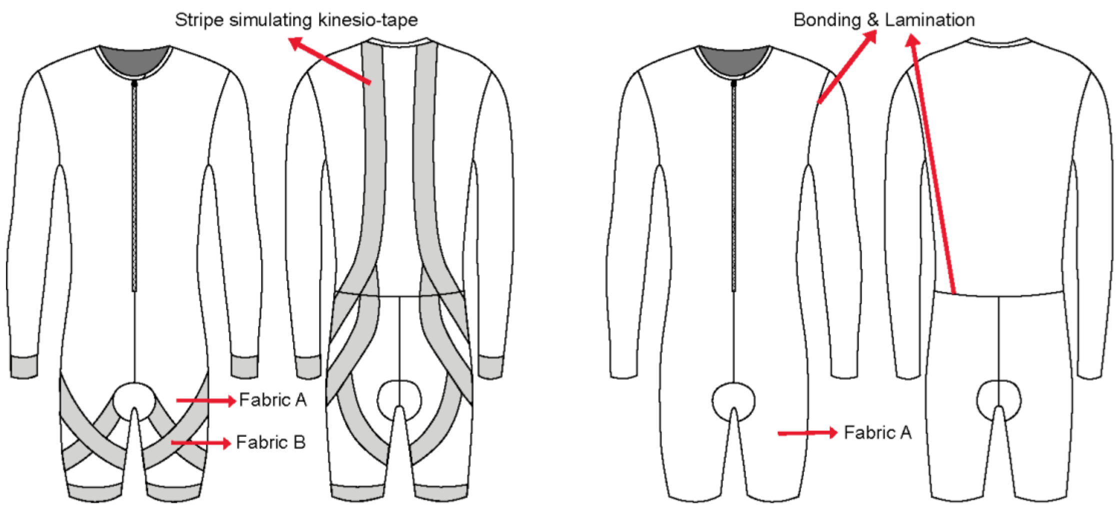
Participants

Eleven male amateur cyclists (age: 27.2 ± 4.4 years; height: 172.3 ± 3.6 cm, body mass: 63.9 ± 6.7 kg; BMI: 21.5 ± 1.9 kg/m^2) were recruited through an amateur cycling association to participate in this study. They were asked to sign a consent form prior to the experiment after the experiment procedure briefing. Human subject ethics approval was granted by The XXX University Ethics Committee (HSEARS20180606002). The participants had over six years of cycling experience and they did 4-5 sessions of weekly physical training including cycling which lasted 2-4 hours per session.

Participants were invited to a fitness testing session one week prior to two experiment sessions and were briefed for the experiment procedure. The participants' body measurements were collected by means of a body scanner and divided into three size groups (i.e., small, medium, large) according to height and chest circumference for garment allocation. The participants were required to refrain from drinking caffeine or stimulants for a period of 24 hours before they participated in the tests. Either CCS or CG was worn with randomized order for each session of the experiment. All tests were performed on the same cycle ergometer while the saddle height was adjusted to match the height of each subject. Participants were asked to wear the same pair of sport shoes for both sessions. No water or food was supplied during the experiment.

Garments

A CCS with stripes simulating kinesio-tape was newly designed by the researchers for this study. The experiment garment (i.e., CCS) and the control garment (i.e., CG) were identical except for the stripes simulating kinesio-tape. They were one-piece garment composed of a top with long sleeves and knee-length shorts. CCS and CG were made of the same weight knit fabric (218g/m^2, Sensitive® Fabrics, Eurojersey, Italy) while a double-side adhesive film (8120 Bidream light, Framis Italia, Italy) was used to bond the stripes simulating kinesio-tape on to the CCS. Both garments were fabricated by a factory. The sew-free technologies (Macpi, Italy) including bonding and lamination were utilized for the garment construction. The CCS with stripes simulating kinesio-tape and CG are shown in Figure 1. Patterns of CCS and CG were drafted by applying a 20% of negative ease on the course direction, which contributed to the compression power.[22,23]



(a) CCS (b) CG

Figure 1. Technical drawings of CCS and CG with details

Table 1 shows the physical properties of the materials used in this study. The uniaxial tensile test was carried out on an INSTROM-4411 tensile test machine (CRE type) according to ASTM D4964-96. The sample size was set to 50 mm wide × 100 mm length in loop form.[24] The loading and unloading crosshead speed was 500 mm/min. Results were used to investigate the elastic properties of test samples.

Table 1. Physical property summary of the used materials

Material	Fabric A	Fabric B	Fabrics A + B	Adhesive Film
Usage	Main Fabric	Simulating kinesio-taping	Simulating kinesio-taping	Bonding
Content	59% polyamide + 41% elastane	73% polyamide + 27% elastane		100% Polyurethane
Thickness (mm)	0.52	0.39	0.86	0.13
Weight (g/m^2)	218	117		150
Density (g/m^2)	27 (wale) 27 (course)	27 (wale) 27 (course)		
Air permeability (kPa・m/s)	0.087	0.225	0.001	
Qmax (w/cm^2)	186.4	169	186.4	
Water vapor transmission rate	3.9	4.1	0.2	

(g/m²/day)			
E_x (kPa)	433.0	930.0	1848.4
E_y (kPa)	231.2	244.3	2374.4

Note. E_x indicates course direction. E_y indicates wale direction.

Experiment protocol

The controlled laboratory's ambient temperature and relative humidity were 23 °C and 50% respectively. A Monark cycle ergometer (Ergomedic 894E, Vansbro, Sweden) equipped with a digital speedometer and a 0.5 kg weight basket was used for the experiments. The load was set as zero with the weight basket. The participants changed into the testing garment upon their arrival at the laboratory (Figure 2). Seat height was adjusted by setting the knee flexion at 25 degrees at the dead bottom center of the pedaling stroke.[25]

(a) CCS (b) CG

Figure 2. Experimental garments

The experiment protocol was shown in Figure 3. Participants were asked to sit in a static sitting position for 30 seconds for the pressure data collection before 5-minute warm-up cycling in a bending posture with their elbows leaning on the handlebar at a cadence of 30-40 rpm. After warm-up, the participants performed a twelve sets of short-term cycling combination of three workloads and four cadences. The three workloads included low (i.e., 1 kg), medium (i.e., 1.5 kg), and high workloads (i.e., 2 kg), with a 30-seconds resting period between each workload. The testing order of workload for each subject was randomized so to minimize the possible order effect (e.g., fatigue and familiarization).

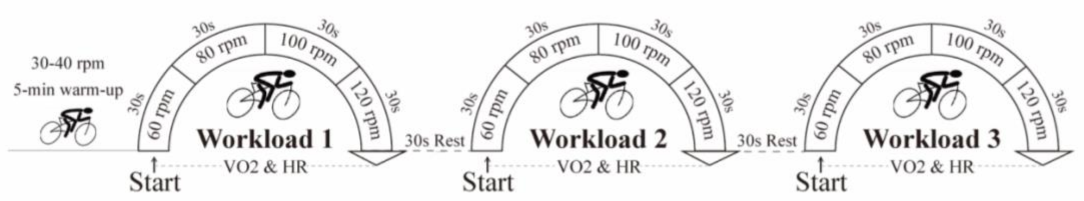


Figure 3. Experiment protocol

Table 2. Testing combinations

Time (second)	Workload (kg)	Cadence (revolution per minute (rpm))			
300	0.5	30-40 (Warm-up)			
120 (30s/rpm)	1	60	80	100	120
120 (30s/rpm)	1.5	60	80	100	120
120 (30s/rpm)	2	60	80	100	120

During each workload, the subject cycled at four different cadences for 30 seconds per cadence, which included low cadence of 60 rpm, medium cadence of 80 rpm, and high cadences of 100 rpm and 120 rpm (see Table 2). The subject was requested to keep the pedaling cadence consistent during the test by following the sound of a metronome and the visual signal on the cycle ergometer's screen.

Pressure measurement

The garment pressure values were collected by the Tactilus Compression Sensor System (Sensor Product Inc, USA). Figure 4 shows the pressure sensor locations on the skin of five muscles including rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF) and semimembranosus (SemM). RF, VL and VM are the front upper thigh muscles. BF and SemM are the back upper thigh muscles. All the selected muscles were the known prime muscles for cycling according to the previous studies.[26,27] The intra-class correlation coefficients for pressure measurements were between 0.85 and 0.92 by single measurements with 95% confidence interval.

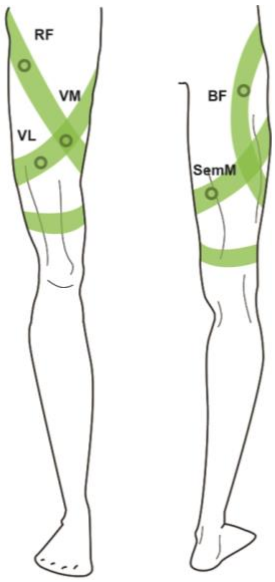


Figure 4. The sensor locations on skin

The pressure data were collected from two settings; 1) a 30-second static sitting before warm-up and 2) a twelve sets of short-term cycling combination of three workloads and four cadences. Each combination lasted for 30 seconds. Pressure values were collected at a rate of sixty frames per second. Mean peak pressure values were calculated and used for statistical analysis.

Physiological measurement and equipment

A cardiopulmonary exercise test system (COSMED® Quark CPET, Rome, Italy) was used to analyze the expired breath (i.e., oxygen and carbon dioxide), which was calibrated before each test according to the manufacturer's instructions while the turbine flowmeter was calibrated by using a 3-L syringe. VO_2 data was continuously recorded. HR was continuously monitored and recorded at a frequency of 1Hz by a HR sensor (Polar H10, Polar Electro Oy, Kempele, Finland). Mean VO_2 and HR values of each combination of workload and cadence were calculated for statistical analysis.[2,28] The intra-class correlation coefficients for HR and VO_2 were 0.94 and 0.91 respectively by single measurements with 95% confidence interval.

Statistical analyses

SPSS software (SPSS Statistics IBM, Version 20.0) was used test for statistical significance. A 2 (garment) $\times$ 3 (workload) factorial analysis of variances (ANOVA) with two-way repeated measures was employed to examine their effects on pressure value, VO_2, and HR at four different cadences (i.e., 60 rpm, 80 rpm, 100 rpm and 120 rpm). Statistical significance was set at $P < 0.05$, and significant level of $P < 0.001$ was also indicated in the related figures and tables. If the significance was found, post-hoc test with Least Significant Difference (LSD) was employed to identify the difference between conditions. Effect size was quantified by using partial eta squared (η_p^2).[29] All the data was presented in mean and standard deviation (SD) (i.e., mean (SD)).

Results

Pressure measurements during static sitting

Figure 5 shows the pressure values of CCS and CG that were measured in the static sitting posture. Statistical analysis showed pressure values of RF, VL, VM and BF were significantly higher when wearing CCS. However, no significant difference was found between garments at SemM.

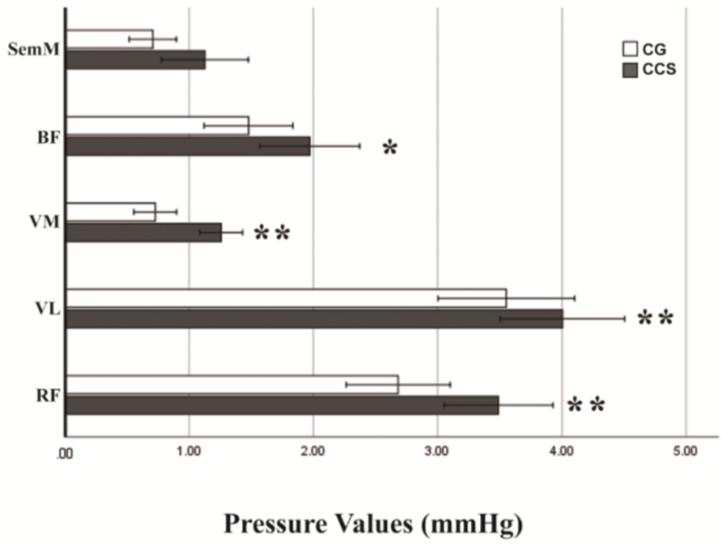


Figure 5. The pressure values with two garments in static sitting posture. * indicates $P < 0.05$, significant difference from CG. ** indicate $P < 0.001$, very significant difference from CG. VL indicates vastus lateralis. VM indicates vastus medialis. BF indicates biceps femoris. SemM indicates semimembranosus.

Pressure value comparisons between two garments at each muscle (CCS vs. CG) were RF (3.5 (1.5) vs. 2.9 (1.4) mmHg, $P = 0.001$); VL (4.0 (1.7) vs. 3.6 (1.8) mmHg, $P = 0.001$); VM (1.3 (0.6) vs. 0.7 (0.6) mmHg, $P = 0.000$); BF (2.0 (1.3) vs. 1.5 (1.2) mmHg, $P = 0.013$); and SemM (1.1 (1.2) vs. 0.7 (0.6) mmHg, $P = 0.106$).

Pressure measurements during cycling

According to the results of two-way repeated measures ANOVA, the factors of garment and workload have a significant interaction effect on the BF's pressure values at 80 rpm ($F(2,20) = 4.087$, $P = 0.032$, $\eta_p^2 = 0.290$), at 100 rpm ($F(2,20) =$

11.581, $P = 0.004$, $\eta_p^2 = 0.537$), at 120 rpm ($F(2,20) = 9.817$, $P = 0.001$, $\eta_p^2 = 0.495$) whereas there was no significant interaction effect on the pressure values for other muscles ($P > 0.05$). CCS provided significantly higher pressure values than CG on three muscles (i.e., RF, VL, and BF) ($P < 0.05$) during all three workloads cycling while VM ($P < 0.05$) showed significantly higher pressure values only during low workload cycling (see Table 3).

Table 3. Statistical results of pressure intensity at thigh (mmHg)

Muscle Point	Workload	CCS				CG				Statistical Results	
		60 rpm	80 rpm	100 rpm	120 rpm	60 rpm	80 rpm	100 rpm	120 rpm	P value	η_p^2
RF	Low	27.5 (11.5) **	29.1 (11.4) **	29.8 (11.2) **	28.9 (13.0) *	10.3 (3.3)	10.4 (3.2)	10.6 (2.6)	11.8 (3.7)	**<0.001****	0.709
	Medium	29.0 (14.4) *	30.3 (16.1) *	29.2 (13.8) *	30.4 (16.4) *	10.7 (5.3)	13.7 (4.7)	14.7 (5.1)	14.5 (5.9)	**0.003 ***	0.567
	High	29.7 (8.7) **	30.1 (12.0) *	32.4 (13.7) **	26.4 (14.2) *	13.5 (5.2)	13.7 (7.0)	13.2 (5.4)	13.5 (6.3)	**<0.001****	0.739
VL	Low	22.2 (5.3) *	21.2 (4.7) *	21.2 (4.3) *	22.1 (6.3) *	14.2 (5.7)	14.2 (4.8)	12.7 (5.7)	13.6 (4.6)	**0.007 ***	0.515
	Medium	25.1 (7.4) *	25.1 (7.4) *	25.5 (9.3)	25.1 (7.3) *	18.8 (4.9)	18.8 (4.9)	19.0 (3.4)	18.3 (4.4)	**0.044 ***	0.346
	High	24.4 (7.5) *	24.3 (8.6) *	23.7 (7.8) *	25.7 (8.2) *	17.7 (2.9)	17.1 (3.4)	16.9 (3.9)	17.1 (3.8)	**0.025 ***	0.410
VM	Low	9.9 (5.8)	10.2 (4.7) *	8.1 (3.5) *	8.6 (4.8)	6.0 (3.2)	6.0 (2.5)	4.4 (3.0)	5.7 (2.4)	**0.040 ***	0.369
	Medium	11.7 (5.4)	11.5 (5.1)	11.2 (5.0)	11.0 (5.5)	6.6 (3.7)	7.6 (4.9)	7.0 (4.7)	6.8 (5.0)	0.055	0.320
	High	10.1 (4.3)	10.1 (3.4)	9.6 (3.9)	9.7 (3.6)	7.6 (2.4)	8.2 (2.9)	8.5 (3.2)	7.9 (3.7)	0.129	0.215
BF	Low	12.1 (10.3) *	12.2 (10.5) *	11.8 (8.1) *	12.2 (8.5) *	5.6 (4.3)	5.5 (4.8)	6.2 (5.4)	5.7 (5.3)	**0.029 ***	0.366
	Medium	17.0 (10.2) **	17.4 (10.6) **	17.4 (10.1) **	20.0 (9.5) **	5.4 (4.6)	5.5 (4.7)	6.5 (5.6)	5.6 (4.8)	**<0.001****	0.778
	High	15.7 (8.1) *	15.8 (8.6) *	16.4 (9.1) **	17.5 (9.9) **	5.7 (5.7)	6.6 (5.3)	7.0 (5.7)	5.2 (5.2)	**0.001 ****	0.702
Se mM	Low	8.4 (8.1)	8.3 (8.5)	8.2 (6.6)	8.7 (8.6)	5.4 (4.1)	5.4 (4.7)	5.4 (5.1)	5.9 (4.3)	0.255	0.161
	Medium	9.5 (9.0)	10.3 (8.6)	9.3 (7.1)	9.4 (7.8)	7.9 (5.6)	10.0 (7.5)	9.6 (8.3)	9.6 (7.3)	0.881	0.002
	High	9.9 (9.7)	8.9 (7.9)	9.1 (7.6)	9.0 (6.8)	8.8 (6.6)	8.9 (5.6)	7.9 (5.0)	8.5 (5.4)	0.782	0.008

Note. * indicates $P < 0.05$, significant difference from CG. ** indicate $P < 0.001$, very significant difference from CG. RF indicates rectus femoris. VL indicates vastus lateralis. VM indicates vastus medialis. BF indicates biceps femoris. SemM indicates semimembranosus.

Figures 6-10 show the post-hoc results of pressure values of CCS and CG during different combinations of workload and cadence. Regardless of cadence during three workloads, CCS provided significantly higer pressure values to the front upper thigh muscles including RF ($P < 0.05$) (Figure 6), VL ($P < 0.05$, except for medium workload at 100 rpm)) (Figure 7), and the back upper thigh msucle, BF, ($P < 0.05$) (Figure 9). The pressure values of VM (Figure 8) induced by CCS were significantly higher at 60 and 80 rpm ($P < 0.05$) during low workload cycling when compared with pressure values of CG. However, there was no significant difference in SemM (Figure 10).

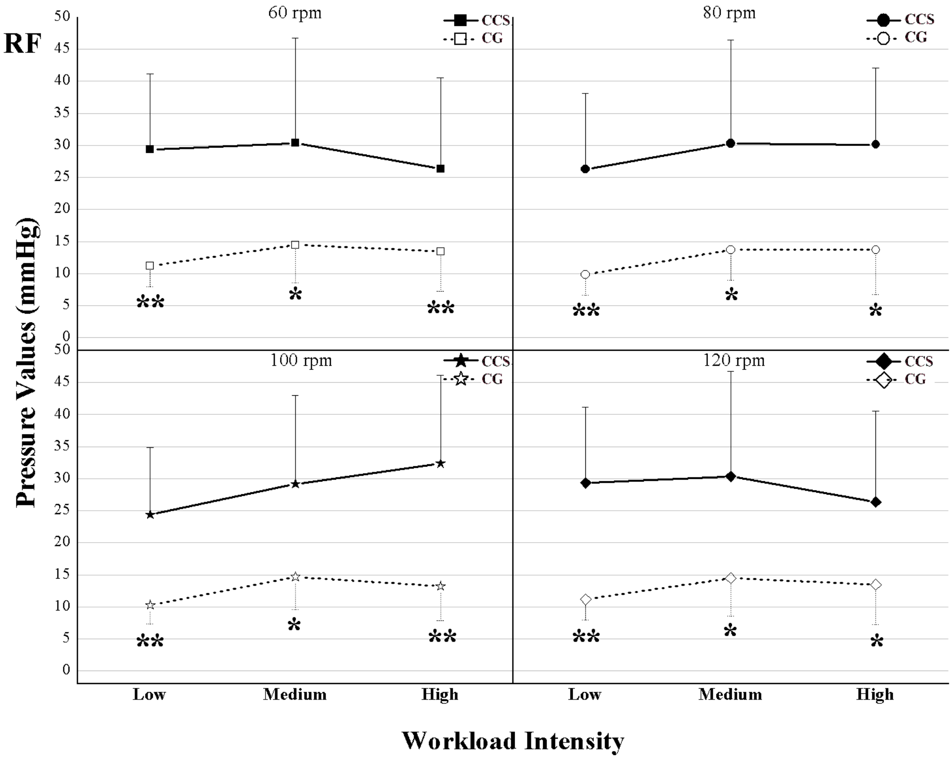


Figure 6. The pressure values of rectus femoris (RF) with two garments during cycling. * indicates $P < 0.05$, significant difference from CG. ** indicate $P < 0.001$, very significant difference from CG.

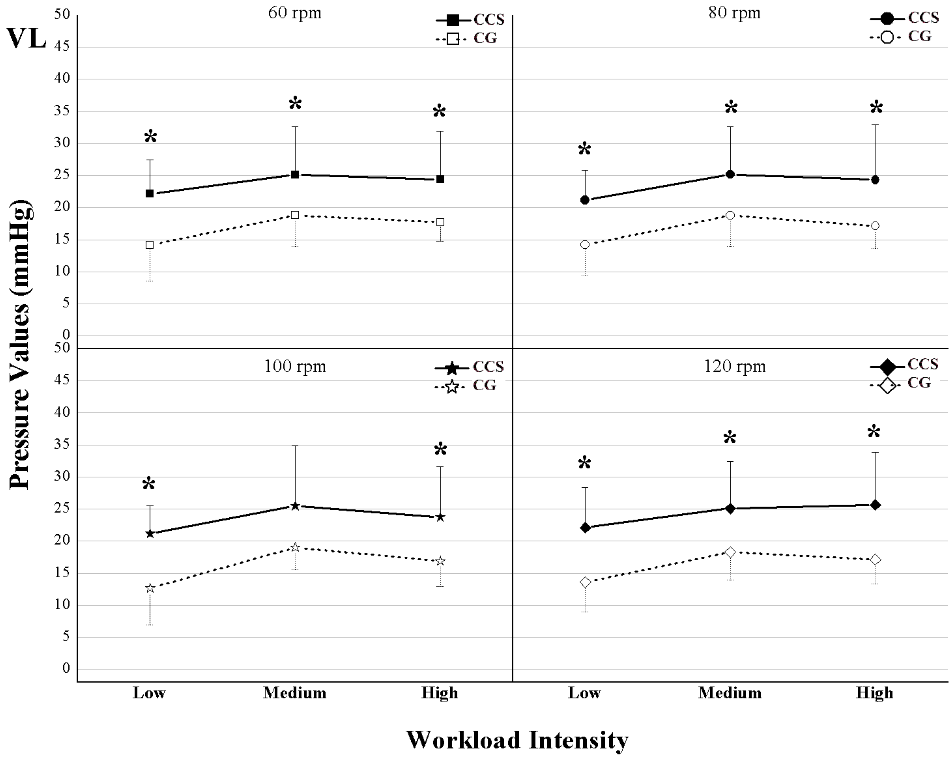


Figure 7. The pressure values of vastus lateralis (VL) with two garments during cycling. * indicates $P < 0.05$, significant difference from CG.

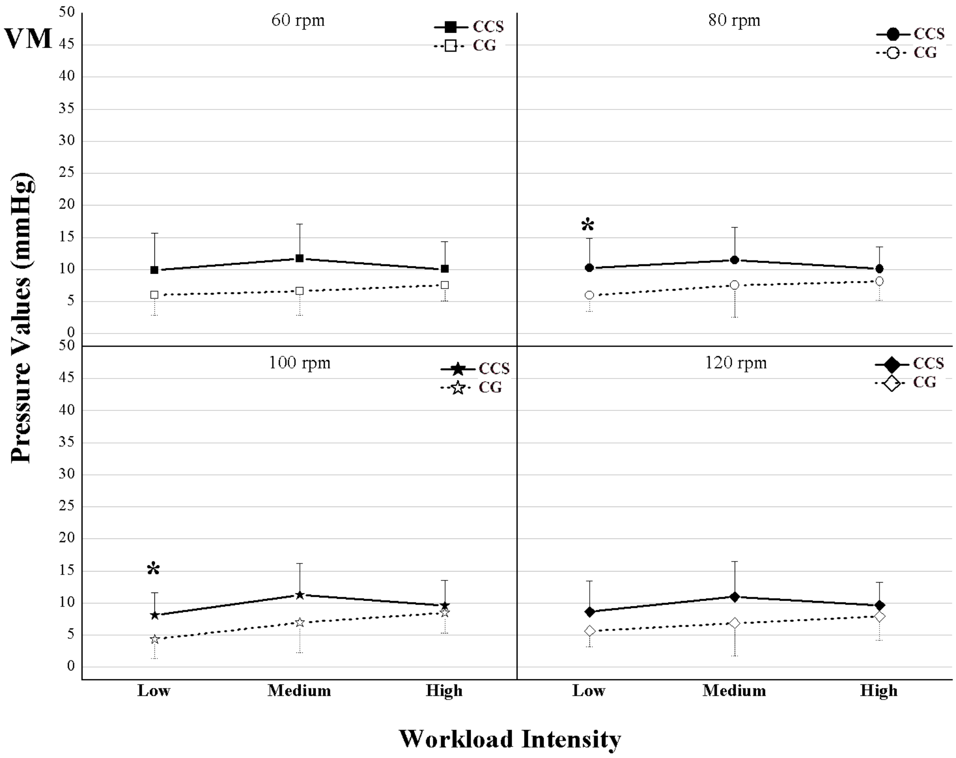


Figure 8. The pressure values of vastus medialis (VM) with two garments during cycling. * indicates $P < 0.05$, significant difference from CG.

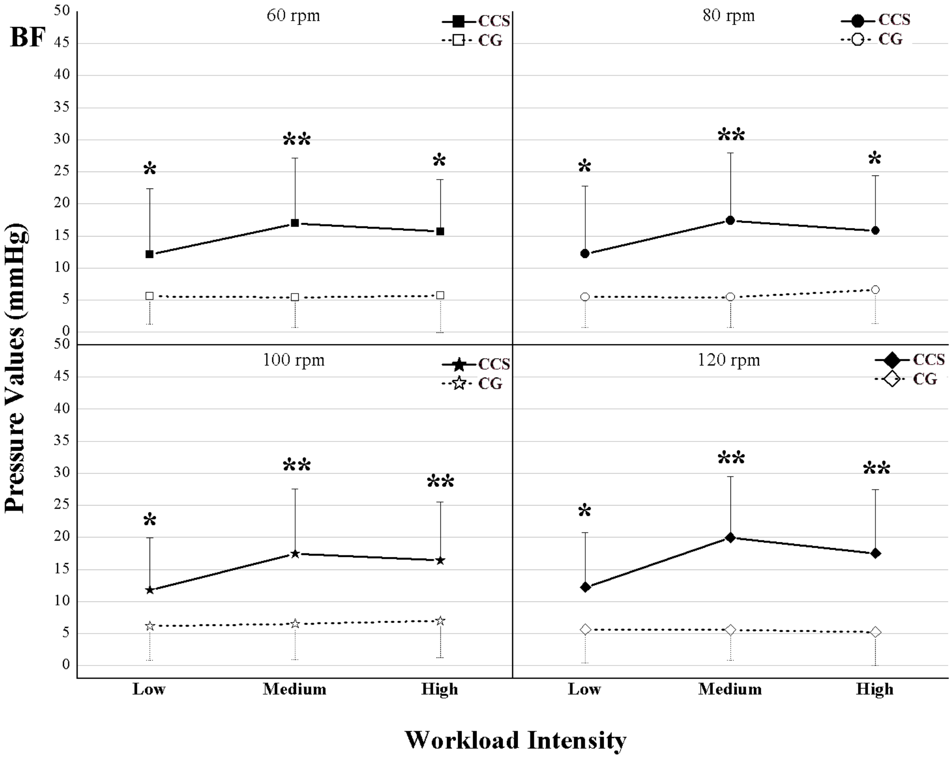


Figure 9. The pressure values of biceps femoris (BF) with two garments during cycling. ** indicates $P < 0.05$, significant difference from CG. ** indicate $P < 0.001$, very significant difference from CG.

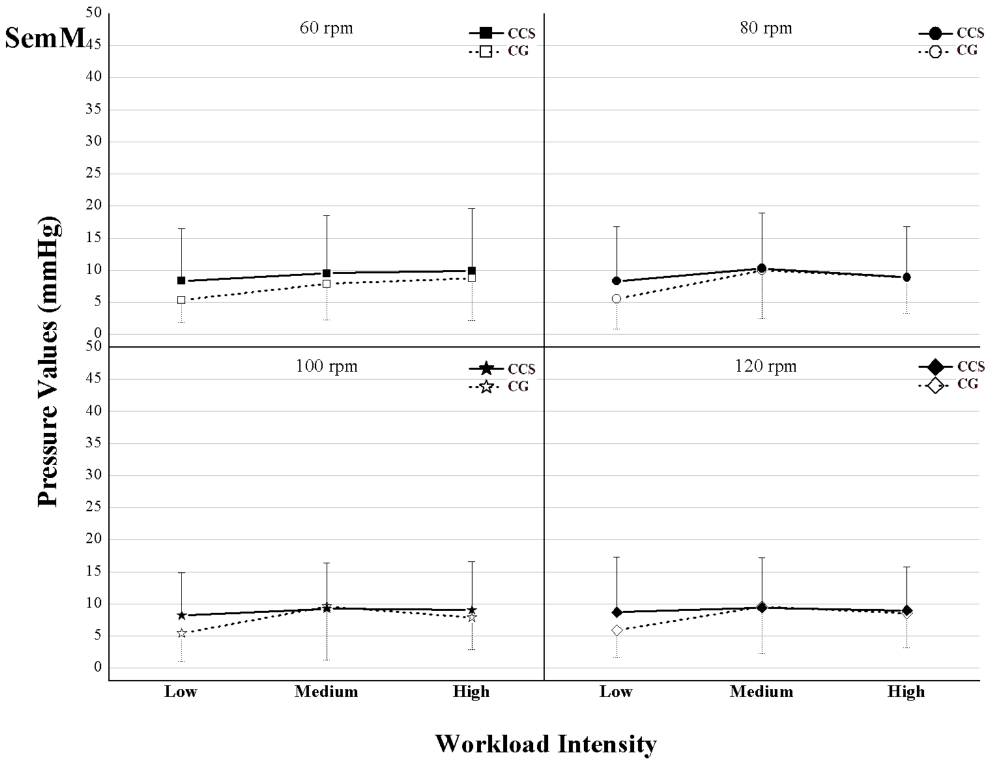


Figure 10. The pressure values of semimembranosus (SemM) with two garments during cycling.

Among the five muscles, RF and BF showed bigger pressure value differences between CCS and CG. Pressure values of CCS at RF and BF ranged from 26.4 (14.2) to 32.4 (13.7) mmHg and 11.8 (8.1)-20.0 (9.5) mmHg respectively during cycling with three different workloads (see Figures 6 & 9).

VO_2 measurements during cycling

Statistical analysis results showed that there was a significant interaction effect of garment and workload on VO_2 (ml/kg/min) during cycling at high cadence (i.e., 120 rpm) ($F(2,20) = 6.803$, $P = 0.006$, $\eta_p^2 = 0.405$).

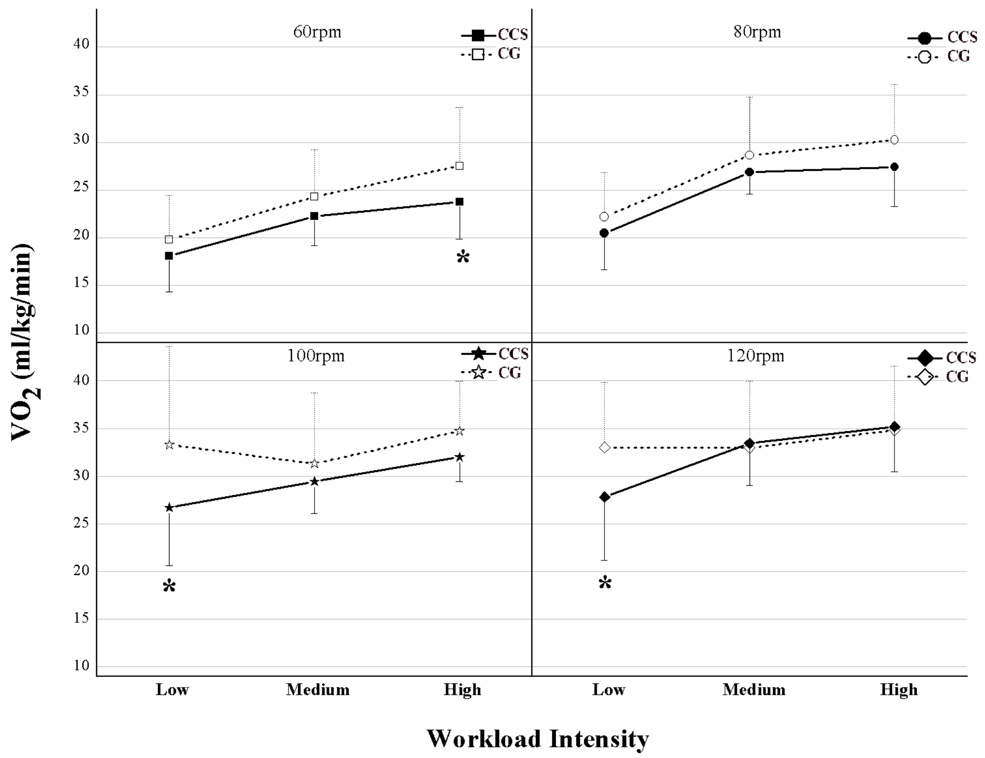


Figure 11. VO_2 of eleven participants with two garments during cycling. * indicates $P < 0.05$, significant difference from CG.

Mean VO_2 values (SD) of all participants wearing two garments are presented in Figure 11 and Table 4. It was observed that VO_2 increased as workload increased at all cadences when wearing either garment. In addition, VO_2 increased as cadences increased when cycling with the same workload. The VO_2 ranges (CCS vs. CG) included: 1) with low workload, 18.1 (3.8)-27.8 (6.6) vs. 19.8 (4.7)-33.0 (6.0); 2) with medium workload, 22.3 (3.1)-33.4 (4.4) vs. 24.3 (4.9)-33.0 (7.0); and 3) with high workload, 23.7 (3.9)-35.2 (4.7) vs. 27.5 (6.1)-34.8 (6.7). VO_2 was significantly lower when the participants wearing CCS and cycled with low workload at high cadence (100 and 120 rpm) ($P < 0.05$) or cycled with high workload at low cadence (60 rpm) ($P < 0.05$). There was no statistically significant difference found in other combinations (see Table 4).

Table 4. Statistical results of VO_2 (ml/kg/min) and heart rate (HR) (bpm) at all cadences.

	Workload	CCS				CG				Statistical Results	
		60 rpm	80 rpm	100 rpm	120 rpm	60 rpm	80 rpm	100 rpm	120 rpm	P value	η_p^2
VO_2	Low	18.1 (3.8)	20.5 (3.8)	26.7 (6.1) *	27.8 (6.6) *	19.8 (4.7)	21.2 (4.6)	33.3 (10.3)	33.0 (6.0)	**0.014***	0.498
	Medium	22.3 (3.1)	26.9 (2.3)	29.4 (3.3)	33.4 (4.4)	24.3 (4.9)	28.7 (6.1)	31.3 (7.4)	33.0 (7.0)	0.481	0.051
	High	23.7 (3.9) *	27.4 (4.2)	32.0 (2.6)	35.2 (4.7)	27.5 (6.1)	30.3 (5.8)	34.7 (5.3)	34.8 (6.7)	0.186	0.168
HR	Low	113 (14)	120 (16)	128 (17)	138 (19)	118 (10)	122 (12)	130 (11)	142 (14)	0.235	0.224
	Medium	128 (12)	133 (16)	139 (16)	148 (19)	131 (12)	137 (12)	144 (13)	152 (13)	0.237	0.136
	High	124 (14) *	133 (15) *	140 (16) *	152 (16)	131 (10)	139 (11)	147 (13)	157 (14)	**0.035 ***	0.373

Note. * indicates $P < 0.05$, significant difference from CG.

HR measurements during cycling

Statistical analysis results showed that there was no significant interaction effect of garment and workload on HR during cycling (P > 0.05) while CCS had significant influence on HR during high workload cycling by ($F(1,10) = 5.959$, $P = 0.035$, $\eta_p^2 = 0.373$).

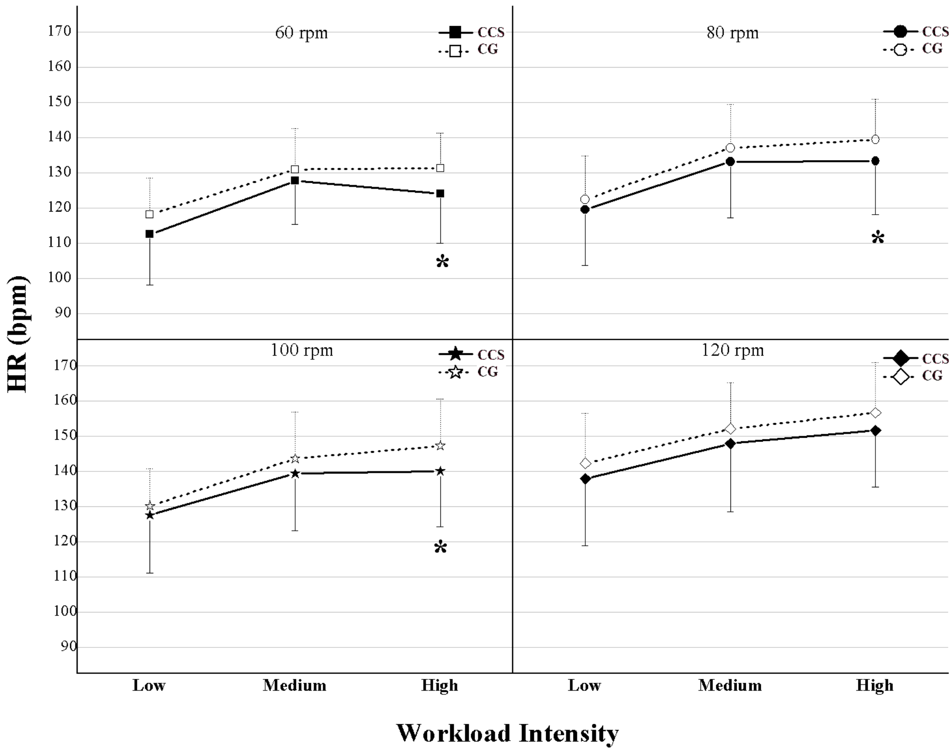


Figure 12. HR of eleven participants with two garments during cycling. * indicates $P < 0.05$, significant difference from CG.

Mean HR values (SD) of all participants between two garments are presented in Figure 12 and Table 4. It was observed that HR increased as workload increased at all cadences when wearing either garment. However, HR increment rate slowed down when cycling between medium and high workload. In addition, HR increased as cadences increased when cycling with the same workload. The HR ranges (CCS vs. CG) included: 1) low workload, 113 (14)-138 (19) vs. 118 (10)-142 (14); 2) medium workload, 128 (12)-148 (19) vs. 131 (12)-152 (13); and 3) high workload, 124 (14)-152 (16) vs. 131 (10)-157 (14). In particular, the mean HR was around 3% lower when participants were wearing CCS and cycled with high workload. HR was significantly lower when the participants wore CCS and cycled with high workload at all cadences ($P < 0.05$) except that of 120 rpm (see Figure 12).

Discussion

This was the first study to investigate the influences of CCS with stripes simulating kinesio-tape on energy consumption during cycling with different workloads at different cadences. In addition, the pressure values of the garment tested were measured during the exercise whereas a majority of studies utilized the pressure value given by CG manufacturers for the data collection and analysis.

The main finding was that CCS provided significantly higher pressure to the thigh muscles during both static sitting and cycling compared with CG while VO_2 and HR of participants who wore CCS were generally lower than those of CG. This supported H1 and H2 although the pressure values varied.

Unlike the previous studies investigating kinesio-tape effects,[30,31] the locations of the stripes simulating kinesio-tape applied on CCS were strategically decided based on the locations of the major cycling contributing muscles (i.e., RF, VL, VM, BF & SemM). The design innovation to provide extra pressure by the stripes simulating kinesio-tape to all contributing thigh muscles was proven to be effective in terms of saving energy for the same power output, in particular during the short-term all-out cycling. It was in line with the previous study's finding that the activation of both anterior and posterior thigh muscles was an important performance factor for intense cycling.[26]

Except for SemM, pressure values of RF, VL, VM, and BF were significantly increased when CCS was worn regardless of the cycling intensity. Among the five muscles, RF and BF showed the largest differences of pressure values between CCS and CG, which was consistent with the expectation of CCS's design innovation. RF required more support from the garment during cycling because the RF muscle had a greater activation of muscle fibers and began to fatigue earlier than the other quadriceps femoris muscles.[26] When more support was provided to RF during cycling, the activity of the RF increased, which led RF to generate more power with the same energy.[32] In the current study, CCS provided the highest average pressure value to the RF (27.5 (12.5) mmHg) of all the five muscles. RF's pressure range was within the most effective range for muscle activation, medium pressures (25.1-32.1 mmHg), which was claimed by the previous studies.[33,34] Similar to RF, BF was reported to have decreased its activity significantly with the repetition of cycling sprints.[35] The reason was that its location (i.e., posterior thigh), BF was not easily triggered by CG during cycling. However, it could be deduced that CCS might have promoted muscle activities with its significantly increased pressure. Thus, it could be deduced that CCS's stripes simulating kinesio-tape contributed to RF's and BF's muscle activation during cycling.

Differences in pressure values between CCS and CG on thigh muscles were also linked to the changes in blood flow. The CCS's stripes simulating kinesio-tape further improved the venous return by providing additional pressure to the CG's extravascular pressure. When the improved venous return enhanced the stroke volume and cardiac output, VO_2 and HR were reduced.[3,5] VO_2 and HR were used as essential physiological markers to quantify the power output which related to energy consumption during cycling.[11] In the study under discussion, a complex relationship between garment condition, power output, workload and cadence emerged, which the energy reduction evidenced by reduced VO_2 and HR proved the CCS's impact on stroke volume and cardiac output enhancement. Even though different cycling combinations generated the same power outputs, not all cycling combinations used had have the statistical significance. For instance, in the present study, three cycling combinations (i.e., 1 kg × 120 rpm, 1.5 kg × 80 rpm, 2 kg × 60 rpm) generated the same power outputs (i.e., 58.8 watts) but only two cycling combinations, the low workload with high cadence (i.e., 1 kg × 120 rpm) and the high workload with low cadence (i.e., 2 kg × 60 rpm), showed statistical significance in VO_2. According to the participants, it was harder to maintain the consistent cadence control when cycling with low workload at high cadence or high workload at low cadence than other cycling combinations. This was in line with the findings of other studies, which indicated that the participants became tired quicker when they cycled with high workload at lower cadence.[36]

Although there were studies reporting the positive influence of the CG application on the physiological responses and subsequent cycling performance during short-term high-intensity exercise,[37] very few studies among those reported the significant impacts of CG on VO_2 and HR. Because the present study yielded low VO_2 and HR, it could be deduced that CCS induced the redistribution of blood from the superficial to the deeper venous system by improving muscle pumping and pressure values.

In addition to the improved venous return, the energy saving could be achieved by preventing the excessive muscle vibration during cycling. According to the previous studies, the increased muscle vibration during the intense exercise required more rigorous cardiorespiratory and metabolic outputs[38,39] while the kinesio-tape and a lower-body CG reduced the energy consumption by limiting the muscle activation and vibration.[29,40] Heart rate and energy consumption were highly correlated. Thus, the additional pressure values applied on the thigh muscles by CCS's stripes simulating kinesio-tape might have reduced the muscle vibration and energy consumption by enhancing the effectiveness of muscles activities during cycling, in particular high workload cycling. The significant effects of CCS on HR were found during high workload at 60 rpm, 80 rpm and 100 rpm cadences except 120 rpm. HR of CCS was 3% lower than that of CG during the high workload cycling. This was in line with a previous study which found that CG with a medium pressure range (i.e., 20 & 40 mmHg) was found to reduce the muscle vibration by 20-25.5% during short-term skiing.[40] There was no significant difference found on HR induced by a cycling combination of high workload at the highest cadence 120 rpm. It might have been that too strenuous muscle vibration hindered the impact of CCS's pressure on physiological responses during the high-workload and high-cadence cycling.

CCS induced better venous return and less muscle vibration due to effectively higher compression power. The potential limitation of this study is the CCS's effect on the endurance cycling performance with different workloads and cadences are needed. In conclusion, the newly designed CCS with stripes simulating kinesio-tape was effective in energy conservation during short-term cycling especially for high workload cycling in comparison with the conventional CG, which supported H3. Further study is required to investigate the direct relationship between pressure values and the physiological responses during cycling with different workloads and cadences.

Conclusion

This study shed light on the influence of compression garments with stripes simulating kinesio-tape on the compression, physiological responses at different workloads and cadences during cycling. CCS reduced energy consumption during cycling due to the effective compression power. There were significant differences in VO_2 and HR during short-term cycling combinations with different workloads and cadences. CCS facilitated the venous return improvements and muscle vibration attenuation by providing appropriate compression power while positively impacting on the physiological parameters (i.e., VO_2 and HR). Thus, CCS could be useful especially for the sprint (i.e., track cycling) where the cyclists are required to accelerate quickly to a high speed while the experiment protocol of this study could be used for cycling training and competition.

In conclusion, the newly designed CCS with stripes simulating kinesio-tape was effective in energy conservation during short-term cycling in comparison with the conventional CG. Therefore, the CCS design principle and performance assessment protocol introduced in this study could be applied to performance compression sportswear development in particular for high-intensity training.

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