ORIGINAL ARTICLE

The influence of a rocking-motion device built into classic cross-country roller-ski bindings on biomechanical, physiological and performance outcomes

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Abstract

This study aimed to determine whether the recently developed Flow Motion Technology® roller-ski prototype could improve indicators of performance during sub-maximal and maximal cross-country roller skiing. Thirteen national and international cross-country skiers completed 2 experimental trials: 1 with Flow Motion Technology® activated, allowing a rocking motion between the foot and ski binding, and 1 with the foot fixed in a traditional manner. Each trial included 2 sub-maximal bouts using the diagonal-stride and double-poling sub-techniques, as well as a double-poling maximal velocity test and a diagonal-stride 6-min time trial. There were no differences in performance between Flow Motion Technology® and traditional roller skiing during the maximal velocity test or the time trial. However, reductions in mean plantar force during sub-maximal diagonal stride ($p = 0.011$) and ankle range of motion during sub-maximal ($p = 0.010$) and maximal ($p = 0.041$) diagonal stride were observed with Flow Motion Technology® versus traditional roller skiing. This, together with a reduced minimum horizontal distance of the hips in front of the ankles during sub-maximal double poling ($p = 0.001$), indicated impaired technique with Flow Motion Technology®, which may have contributed to the trend for reduced gross efficiency during double poling with Flow Motion Technology® ($_p\eta^2 = 0.214$). Significant physiological differences included a reduced sub-maximal double poling respiratory exchange ratio ($p = 0.03$) and a greater maximal heart rate during the time trial ($p = 0.014$) with Flow Motion Technology®. We conclude that the application of Flow Motion Technology® requires further examination before use in training and competition.

Keywords Equipment · Gross efficiency · Kinematics · Product development · Technique

Abbreviations

CL	Cycle length
CR	Cycle rate
ES	Effect size
FMT	Flow Motion Technology® ski setting

GE	Gross efficiency
HR	Heart rate
HR_{max}	Self-reported maximal heart rate
RER	Respiratory exchange ratio
ROM	Range of motion
RPE	Rate of perceived exertion
SD	Standard deviation
TRAD	Traditional ski setting
TT	Time trial
V_{max}	Double-poling maximal velocity test
$\dot{V}CO_2$	Rate of carbon dioxide production
$\dot{V}_E$	Rate of ventilation
$\dot{V}O_2$	Rate of oxygen consumption
$\dot{V}O_{2peak}$	Maximal rate of oxygen consumption

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1 Introduction

Due to the highly physical and technical nature of classic cross-country ski racing, participating athletes require well-developed physiological and biomechanical systems. Indeed, elite cross-country skiers have been documented to elicit some of the highest maximal oxygen uptake ($\dot{V}O_{2max}$) values, with men attaining > 6 L/min or 80 mL/kg/min and women > 4 L/min or 70 mL/kg/min [1, 2]. Gross efficiency (GE) also plays a key role in endurance performance [3] and has effectively predicted sprint time-trial performance in classic cross-country skiing [4]. GE is influenced by technique efficiency [5], both of which must be optimised to achieve success, especially during the most common classic sub-techniques of double poling and diagonal stride [6]. Roller skiing is commonly used by cross-country skiers, particularly during the seasonal preparation periods, and is considered an effective alternative to on-snow skiing when testing, training and racing [7].

A recent review highlighted that diagonal-stride and double-poling movement cycle length (CL) distinguishes faster from slower skiers [8]. To increase CL at a given velocity, or maintain CL with increased speed or gradient, larger leg and pole forces are required during diagonal stride [9, 10]. Similarly during double-poling, increasing poling force by utilising body mass during the preparation phase [11, 12], and increasing hip and knee flexion during propulsion [13, 14], contribute to increasing CL. With an increased CL, faster skiers appear to employ a lower cycle rate (CR) during sub-maximal diagonal stride and double poling [15]. However, CR increases with increasing speed, resulting in reduced propulsion and recovery (or swing) phase durations [16, 17]. Therefore, to achieve high maximal velocities during cross-country ski races [8], maintaining high peak forces and CL over shorter propulsive phase durations appear key for diagonal-stride and double-poling performance.

Alongside optimised technical and physical capabilities of athletes, equipment modifications that enable athletes to adopt biomechanically favourable positions, such as an extended preparation phase during double poling [11], may further optimise technique efficiency and enhance CL, GE, and performance [18]. For example, changes to the foot binding structure could increase the efficiency of energy transfer from muscular to propulsive force, as demonstrated by the clap-skate-type binding. The clap-skate-type binding system has facilitated increased power development and speed during cross-country skate skiing over 50 m [19], but cycle characteristics and GE were not enhanced [20]. No similar or alternative binding prototypes appear to have been tested for classic cross-country skiing.

A technological advancement recently implemented into a classic roller-ski prototype is the patented *Flow Motion Technology*® (FMT) ski binding [21]. Originally, FMT roller skates were designed to improve ice-hockey players' off-season training by increasing the wheel-to-ground contact time and CL, better simulating on-ice skating. In the roller-ski prototype [22], a two-part chassis is attached between the top of the roller-ski and the binding, with a curved upper cradle rocking against a flat lower part (Fig. 1a). The cradle has a 2-m radius along the rolling surface, enabling a rocking motion during movement cycles. This rocking motion aims to increase the angle between the foot and the ski at full extension, prolonging the preparation phase and increasing propulsive force production. The rocking function can be prevented by inserting wedges between the two chassis parts (Fig. 1b).

This study aimed to investigate the effect of FMT versus the traditional (TRAD) locked-chassis position on biomechanical, physiological and performance measures during treadmill roller skiing. It was hypothesised that FMT would prolong the preparation phase during double poling and foot contact time during diagonal stride, hence increasing propulsive force production. CL and GE were therefore expected to be improved at fixed sub-maximal intensities in both diagonal stride and double poling with FMT, and maximal roller-skiing performance was expected to improve. No differences in other physiological variables between FMT and TRAD were expected.
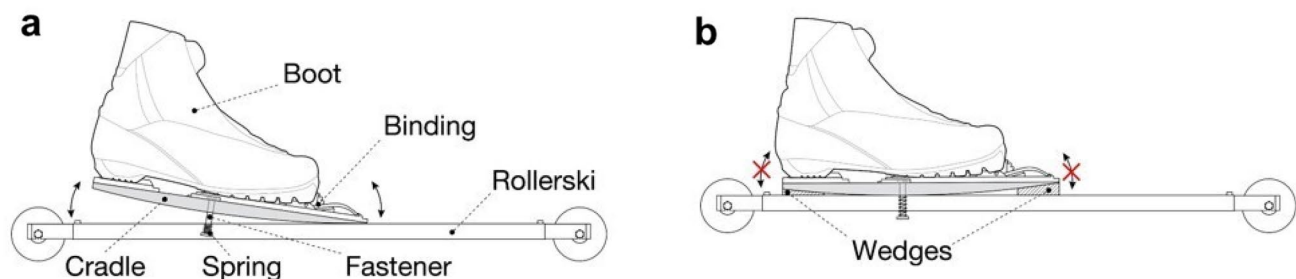

Fig. 1 An illustration of how Flow Motion Technology® (FMT) was implemented into the roller-ski prototype relative to the ski binding and the participant's ski boot showing the freely moving rocking setting (**a**), and the locking of this setting with wedges (**b**)

2 Methods

2.1 Participants

Due to the lack of previous data relating to our hypothesis and methods, no a priori power calculation was conducted, and opportunistic sampling was employed to recruit as many cross-country skiers as possible. All participants were required to be competing nationally (i.e., the Swedish cup) or internationally (i.e., the Ski Classics Pro Tour). Thirteen athletes completed the study (8 men and 5 women; mean $\pm$ SD: age 24 ± 5 years, height 177 ± 11 cm, body mass 72.7 ± 9.9 kg) after providing written informed consent to participate. The study was pre-approved by the Regional Ethical Review Board of Umeå University, Umeå, Sweden (#2018-334-31M) and was conducted in accordance with the Declaration of Helsinki.

2.2 Study overview

Participants visited the laboratory on three occasions within 1 month during the late pre-season period (i.e., October–December). The first visit involved a familiarisation to test procedures. The second and third visits involved two experimental trials where the ski settings (TRAD and FMT) were prescribed in a random order. Participants were instructed to consume a standardised diet and to avoid training, or complete only low-intensity exercise ($< 70\%$ self-reported maximal heart rate [HR_{max}]), on the day before experimental trials. Participants were also instructed to avoid caffeine on the experimental trial days.

2.3 Testing procedures

On arrival at the laboratory, a health questionnaire was completed (online resource 1), followed by measurements of height and body mass (Seca 764, Hamburg, Germany). Exercise tests were conducted on a motor-driven treadmill designed for roller skiing (Rodby Innovation AB, Vänge, Sweden). The same roller skis were used in each trial (Team 610, Elpex Sweden AB, Sweden) with the FMT ski binding [21] incorporated. The rolling-resistance coefficient was measured as (mean $\pm$ SD) 0.018 ± 0.0007 using a previously developed method [23]. The roller skis were pre-warmed at 34 °C for at least 30 min before use to avoid changes in wheel and bearing resistance during exercise. All
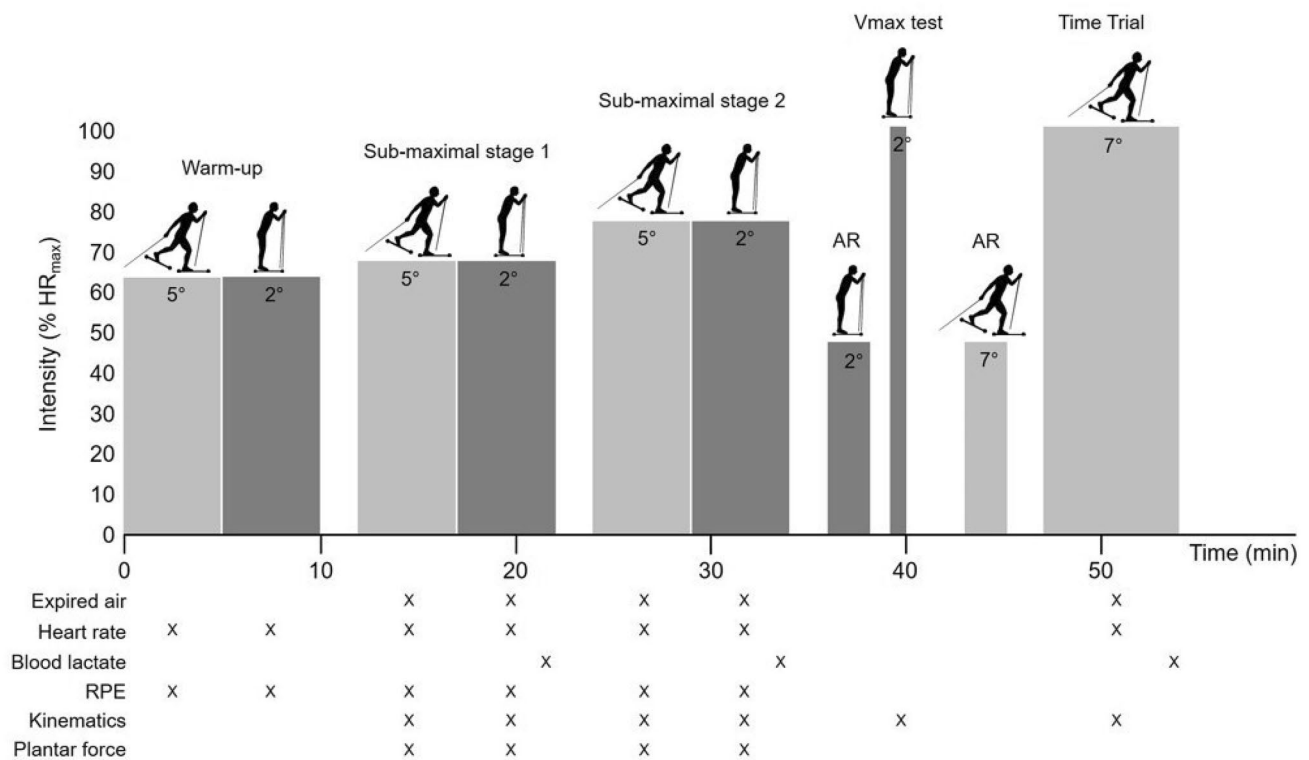

Fig. 2 A schematic of the experimental protocol, including diagonal stride (light-grey) and double poling (dark-grey) sub-maximal stages and maximal tests. The collection of physiological and biomechanical variables is also highlighted with an X. AR; active recovery, RPE; rating of perceived exertion

participants were experienced with treadmill roller skiing before the study.

The familiarisation trial simulated subsequent experimental trials, acquainting athletes with FMT, and establishing the individualised treadmill speeds to achieve the desired intensities for the sub-maximal stages. The experimental trials are illustrated in Fig. 2, commencing with a 10-min warm-up at 65% HR_{max} followed by 2 min of passive rest to fit the breathing mask. Two 10-min sub-maximal stages followed, at ~70% and 80–85% of HR_{max}, which reflected a rating of perceived exertion (RPE; [24]) of 12–13 and 15–16, respectively. 15-s rest periods separated diagonal-stride and double-poling bouts to re-start biomechanical measurements. The breathing mask was removed after the second sub-maximal stage.

Before the double-poling maximal velocity (V_{max}) test, there was 2 min of active recovery, where participants self-selected their speed to achieve ~50% HR_{max} using double poling at a 2° incline (Fig. 2). The V_{max} test began with treadmill speeds of 13 km/h for women and 18 km/h for men and increased by 1 km/h every 4 s, inducing failure within 45–60 s. Participants were instructed to continue until exhaustion, which was determined from video footage when the rear-most roller-ski wheel dropped behind a line marked 2 m from the front of the treadmill. Treadmill speed and elapsed time were concealed from the participants, while standardized verbal encouragement was provided throughout. V_{max} performance was determined by the time to exhaustion.

After 3 min of passive rest and 2 min of active recovery, where participants self-selected their speed to achieve ~50% HR_{max} using diagonal stride at a 7° incline, the breathing mask was re-fitted before the 6-min diagonal-stride time trial (TT). Participants were instructed to immediately increase the treadmill speed from 6 km/h to their chosen pace and to self-adjust speed throughout, aiming to cover as much distance as possible. The self-pacing treadmill system has been reported previously [25]. The treadmill speed and distance travelled were concealed from participants, while time remaining and their position on the treadmill were visible. Standardised verbal encouragement was provided throughout the trial. TT performance was expressed as total distance covered.

2.4 Biomechanical and physiological equipment and measurements

Biomechanical markers were placed on the participants' legs, ski boots and poles (Fig. 3) during the 10-min rest period before exercise testing commenced. Three-dimensional marker positions were recorded using an opto-electronic motion capture system (Qualisys AB, Gothenburg,


Fig. 3 Placement of the 30×12-mm reflective markers on the athletes' joint centres and anatomical locations (**a**, **b**), poles (**c**) and roller skis (**d**), with identical placement on lateral aspects of both the left and right sides. Anatomical locations included anterior and posterior superior iliac spines, femoral greater trochanter and lateral epicondyles, malleolus, heel and toe centre

Sweden) with 12 Miqus M3 cameras (2 mega pixel resolution) placed ~4 m away from the participant, measuring at a sampling rate of 200 Hz. The treadmill space where cameras recorded marker positions was calibrated on the morning of each experimental trial day according to system instructions (Qualisys AB, Gothenburg, Sweden). The mean residual of the calibrations was 0.76 mm. The maximum and minimum angles and range of motion (ROM) were calculated for the ski-cradle (Fig. 4a), knee, hip and ankle joints of each leg, and the hip-ankle distance along the treadmill (Fig. 4b), which was defined as positive with the ankle in front of the hip.

Marker positions were recorded for the first 3 min of the diagonal-stride and double-poling sub-maximal bouts and throughout the V_{max} and TT. Five cycles of each sub-technique were analysed (gaps < 50 ms were filled by linear interpolation using Qualisys Track Manager; Qualisys AB, Gothenburg, Sweden), starting from 2.5-min into each sub-maximal bout, 30-s into the V_{max} and 90-s into the TT. One cycle was defined as the point of right pole-ground contact to the subsequent right pole-ground contact. These cycles were smoothed with a bidirectional fourth-order low-pass

Fig. 4 An illustration of the ski-cradle angle (**a**) and the hip, knee and ankle joint angles and hip-to-ankle distance (**b**) calculated from marker positional data
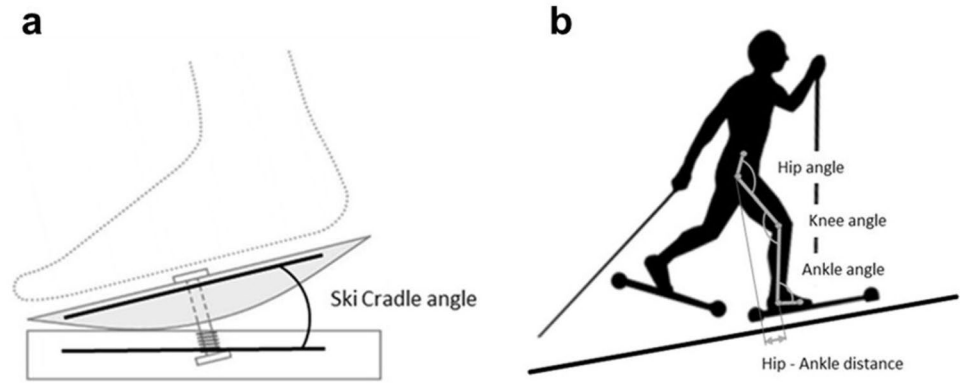
Butterworth filter with a 12 Hz cut off, before joint angles and ROM were calculated in custom MATLAB scripts (Mathworks, version R2019a). This filter was chosen due to the majority of observed frequencies occurring below the cut off (online resources 2a and 2b), with those above likely attributable to noise. The differences in filtered and raw joint angles were also observed to be small (online resources 2c and 2d). Cycle time was also measured, with CL and CR subsequently calculated for diagonal stride and double poling. The mean average was calculated for all variables for both legs, or individual legs were analysed if data was missing due to error. Due to large amounts of noise and loss of marker positions at high skiing speeds (i.e., > 28 km/h), only CL and CR were analysed for the V_{max} test.

Vertical plantar forces were measured at a sampling rate of 50 Hz using pressure insoles (Pedar, Novel GmbH, Germany) inserted into the ski boots in the place of the regular insoles. Each pressure insole was equipped with 84–99 pressure sensors, depending on foot size, and was individually fitted and connected to a data logger around the skier's waist weighing 1.3 kg. Insoles were calibrated before data collection using a Trublu® calibration device (Pedar, Novel GmbH, Germany). Measurement error for this system has previously been measured as − 0.6 to 2.7% under ideal conditions, increasing with increased duration of load application and pressure range experienced [26]. The zero baseline of force was set during the passive rest after the warm-up. Plantar force was measured for the first 3 min of each sub-technique bout, with peak and mean vertical plantar forces calculated for the final minute of measuring (i.e., minute 2–3) for both feet (Pedar, Novel GmbH, Germany). Data was excluded for individual or both feet when many sensors produced erroneous zero values.

For the collection of expired air participants breathed into a face mask (7450 Series V2TM Mask, Hans Rudolph Inc., Shawnee, USA) and breath-by-breath samples were analysed using a portable gas analyser (MetaMax3B-R2, Cortex Biophysik GmbH, Leipzig, Germany). Before each trial, oxygen (O_2) and carbon dioxide (CO_2) sensors were calibrated to ambient air and a 15% O_2 and 5% CO_2 calibration gas (UN 1950 Aerosols, Cortex Biophysik GmbH, Leipzig, Germany). The turbine flow volume was also calibrated with a 3-L syringe (M9474-C, Medikro Oy, Kuopio, Finland). $\dot{V}O_2$, $\dot{V}CO_2$, ventilation ($\dot{V}_E$) and respiratory exchange ratio (RER) were monitored continuously via expired air samples, and HR was monitored continuously using a chest strap and watch (Polar H7, Polar Electro Oy, Kempele, Finland). The accuracy of this device has been compared to ECG during various activities [27], showing small mean absolute differences (0.6–1.2 bpm) and high correlations ($r = 0.99$). Blood lactate concentration was analysed from fingertip blood samples using a Biosen 5140 (EKF diagnostic GmbH, Magdeburg, Germany), calibrated daily with a standardised 12 mmol/L lactate solution. A resting blood sample was taken during a preliminary 10-min rest period, with further samples taken 1 min into the 2-min passive rest period following each sub-maximal stage. Mean $\dot{V}O_2$, $\dot{V}_E$, and RER from 3.5 to 4.0 min in each sub-maximal bout were calculated. HR and RPE were measured after 4 min of each 5-min sub-maximal bout. Mean $\dot{V}O_2$, $\dot{V}_E$, RER and HR were analysed over the entire 6-min TT, while $\dot{V}O_{2peak}$ and HR_{max} were defined as maximum 30-s and 5-s rolling mean averages, respectively. A final fingertip blood sample was taken 1 min after completion. GE (%) was calculated for each sub-maximal bout using a previously described method [4]:

$$GE = 100\frac{PO}{MR_{ae}}, \tag{1}$$

with power output (*PO*) calculated as:

$$PO = Mg\sin(\alpha)v + \mu_R Mg\cos(\alpha)v, \tag{2}$$

where *M* is combined body and equipment masses (kg), *g* is gravitational acceleration (m/s^2), *v* is treadmill speed (m/s), μ_R is the rolling-resistance coefficient and α is treadmill incline (°).

Aerobic metabolic rate (MR_{ae}) was calculated as:

$$MR_{ae} = \frac{4184\dot{V}O_2(1.1RER + 3.9)}{60}, \tag{3}$$

where $\dot{V}O_2$ (L/min) and RER were mean averages from 3.5 to 4.0 min in each sub-technique bout.

2.5 Statistical analyses

Statistical analyses were completed using IBM SPSS Statistics 25 (SPSS Inc. version 25.0; Chicago, IL, USA) with an alpha of 0.05. Assuming the validity of collected data, missing value analyses were conducted for all variables using Little's Missing Completely at Random test [28]. With non-significant differences between observed and estimated means, missing values were determined as random. Therefore, any participant with > 10% missing values for any variable were removed from that variable comparison. Univariate and multivariate outliers were identified with standardised Z scores exceeding 3.29 and Mahalanobis distances exceeding the chi-squared (χ^2) critical value where $p = 0.001$, respectively [29].

All sub-maximal and maximal variables were checked for normality, deemed as violated if skewness or kurtosis values exceeded the standard error multiplied by 3.29, and presented as mean ± SD if normally distributed and median (interquartile range) if violated. For normally distributed sub-maximal variables, two-way paired ANOVAs were conducted separately for double poling and diagonal stride, comparing ski setting (TRAD and FMT) and sub-maximal intensities (sub-maximal stage 1 and 2). In the case of significant interaction effects, Bonferroni post hoc tests were used to analyse paired differences between ski settings and intensities. Effect sizes (ESs) were estimated using partial eta squared values ($_p\eta^2$) and interpreted as small, moderate, or large for $_p\eta^2 \geq 0.01$, 0.06 or 0.14, respectively [30]. The statistical power of each test was estimated with the SPSS syntax function. Friedman rank tests were conducted for non-normally distributed sub-maximal variables, with post hoc Wilcoxon signed rank tests assessing paired differences for ski setting (TRAD versus FMT). Paired-samples t tests were used to analyse differences between TRAD and FMT for normally distributed maximal performance variables. ESs were calculated with Cohen's D for repeated measures (D_{rm}) using an online spreadsheet [31], with small, moderate, large, and very large interpretations for $D_{rm} \geq 0.2$, 0.6, 1.2 and 2.0, respectively [32]. Wilcoxon signed rank tests were used to analyse differences between TRAD and FMT for non-normal maximal performance variables. The statistical power of performance variables was estimated in GPower (version 3.1), with an assumed normal parent distribution for Wilcoxon signed rank test outcomes.

3 Results

3.1 Data analysis

One participant was removed from both sub-maximal and maximal kinematic analyses for double poling and diagonal stride due to a recording error and another failed to complete one TT and was thus removed from the biomechanical and physiological TT comparisons. Participants were removed from comparisons following missing value analysis, with the cause of missing values often equipment error (e.g., erroneous zero values for double-poling plantar force measurements) or human error (e.g., one blood lactate sample was missed). The remaining participants for each comparison (N) and the statistical power of each test are presented in Tables 1, 2, 3, 4 and 5 and Fig. 5.

3.2 Performance responses

The V_{max} test and TT performance results are presented in Fig. 5a, b, respectively. There were no differences between TRAD and FMT for V_{max} test duration ($p = 0.553$) or TT distance covered ($p = 0.331$).

3.3 Biomechanical responses

Biomechanical responses to TRAD and FMT during sub-maximal skiing are presented in Tables 1 and 2 for diagonal stride and double poling, respectively, while V_{max} and TT test responses are presented in Table 3. One significant interaction effect was found between ski condition and intensity for double-poling hip ROM ($F_{1,11} = 5.86$; $p = 0.034$; $_p\eta^2 = 0.348$), with Bonferroni post hoc tests identifying a significant increase from sub-maximal stage 1 to 2 ($p < 0.001$), but no significant differences between ski conditions. The main effects of ski condition during sub-maximal tests showed significantly reduced diagonal-stride ankle ROM ($F_{1,11} = 9.74$; $p = 0.010$; $_p\eta^2 = 0.470$), mean plantar force ($F_{1,10} = 9.69$; $p = 0.011$; $_p\eta^2 = 0.492$), and minimum ski-cradle angle ($F_{1,9} = 41.79$; $p < 0.001$; $_p\eta^2 = 0.823$), alongside double-poling hip-to-ankle distance ROM ($F_{1,11} = 17.76$; $p = 0.001$; $_p\eta^2 = 0.617$) for FMT compared to TRAD. In addition, double-poling minimum hip-to-ankle distance was significantly greater for FMT compared to TRAD ($F_{1,11} = 12.91$; $p = 0.004$; $_p\eta^2 = 0.540$).

Non-parametric analyses revealed a significant effect for ski-cradle maximum angle for diagonal stride ($\chi^2 = 25.56$; $p < 0.001$) and double poling ($\chi^2 = 22.75$; $p < 0.001$), shown in post hoc tests to be significantly greater for FMT in sub-maximal stage 1 (diagonal stride: $p = 0.005$; double poling: $p = 0.003$) and 2 (diagonal stride: $p = 0.005$; double poling: $p = 0.004$). A similar effect was found for ski-cradle ROM
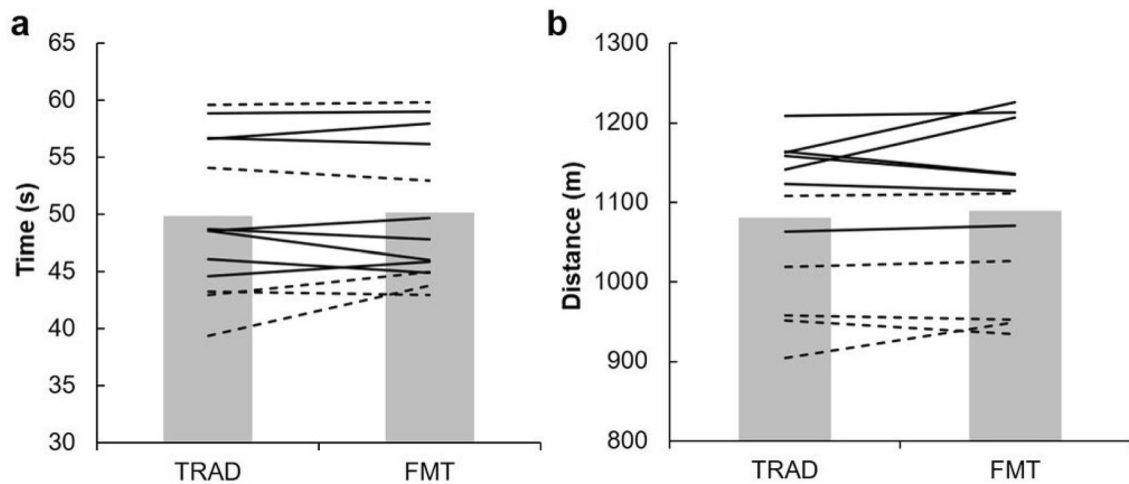
Fig. 5 Time to exhaustion in the maximal velocity (V_{max}) test (**a**; $n = 13$) and distance covered during the 6-min time trial (TT; **b**, $n = 12$) with TRAD and FMT ski settings. Mean values are repre- sented by grey bars, while individual data for women are illustrated with dotted lines and for men with hard lines

for both diagonal stride ($\chi^2 = 28.08$; $p < 0.001$) and double poling ($\chi^2 = 22.75$; $p < 0.001$), with significant increases for FMT revealed in sub-maximal stage 1 (diagonal stride: $p = 0.005$; double poling: $p = 0.003$) and 2 (diagonal stride: $p = 0.005$; double poling: $p = 0.004$). A significant effect was also found for double-poling minimum ski-cradle angle ($\chi^2 = 17.95$; $p < 0.001$), with sub-maximal stage 1 ($p = 0.003$) and 2 ($p = 0.010$) significantly lower for FMT. Moreover, a significant effect was found for diagonal-stride maxi- mum ankle angle ($\chi^2 = 24.40$; $p < 0.001$), with significant reductions in both sub-maximal stage 1 ($p = 0.012$) and 2 ($p = 0.023$) revealed for FMT.

During the TT, FMT led to a significant increase in the ski-cradle maximum angle ($p < 0.001$; $D_{rm} = 7.69$) and ROM ($p < 0.001$; $D_{rm} = 4.74$), and significantly reduced the mini- mum angle ($p = 0.003$; $D_{rm} = 2.45$), compared to TRAD. FMT also led to significant reductions in ankle ROM com- pared to TRAD ($p = 0.041$). During the V_{max} test, CL was significantly reduced with FMT ($p = 0.050$; $D_{rm} = 0.44$). No further significant differences were identified during the V_{max} or TT.

3.4 Physiological responses

The physiological responses to FMT and TRAD in both sub-maximal stages are presented in Table 4. No signifi- cant interaction effects were identified between ski setting and intensity. However, main effects for ski setting revealed significantly reduced RER during double poling with FMT versus TRAD ($F_{1,12} = 6.09$; $p = 0.030$; $_p\eta^2 = 0.337$). Further- more, a significant effect was revealed for diagonal-stride GE ($\chi^2 = 8.26$; $p = 0.041$), however, post hoc tests revealed no significant differences between FMT and TRAD during

sub-maximal stage 1 or 2. The physiological responses dur- ing the TT are presented in Table 5. The only significant difference observed between trials was a significantly greater HR_{max} with FMT versus TRAD ($p = 0.014$; $D_{rm} = 0.081$).

4 Discussion

This study investigated whether the FMT roller-ski pro- totype was efficacious in improving classic cross-country roller-skiing performance in well-trained skiers by elicit- ing biomechanically favourable effects, whilst minimising physiological perturbations. Contrary to the hypotheses, FMT provided no significant advantage over TRAD in terms of V_{max} or TT performance. Moreover, there were no sig- nificantly beneficial effects of FMT during diagonal stride or double poling on CL or GE. In support of the hypoth- esis, however, physiological differences between FMT and TRAD were typically not significant. It is clear that FMT enables a rocking motion throughout the movement cycles as designed, evidenced by the significant increases in maxi- mum and minimum angles, and ROM of the ski-cradle in both sub-maximal and maximal diagonal stride and double poling. In relation to this mechanism, several biomechanical differences were observed.

There was a trend for an increased CL during sub-max- imal diagonal stride with FMT in this study, alongside a trend for increased hip-to-ankle distance ROM. CL at sub- maximal and maximal speeds has previously been correlated positively with diagonal-stride time to exhaustion [9] and maximal anaerobic performance [17]. Furthermore, during both sub-maximal exercise and a diagonal-stride V_{max} test, CL was greater among faster versus slower cross-country

Table 1 Biomechanical responses to the two ski settings (TRAD and FMT) at the two sub-maximal exercise intensities (stages 1 and 2) during diagonal stride

	N		Sub-maximal stage 1		Sub-maximal stage 2		Main effect for ski setting				Friedman test
			TRAD	FMT	TRAD	FMT	F ratio	p value	ES ($_p\eta^2$)	Power	
Ski-cradle (°)	10	Max	0.7 (0.6–1.0)	2.6 (2.4–2.7)	0.8 (0.6–0.9)	2.7 (2.5–2.7)	$F_{(1,9)}=41.79$	<0.001*	0.823		<0.001†
		Min	−0.2±0.2	−1.3±0.4	−0.4±0.5	−1.9±0.8				1.000	
		ROM	0.9 (0.8–1.1)	4.0 (3.6–4.2)	0.9 (0.8–1.2)	4.5 (4.1–5.2)					<0.001†
Knee (°)	12	Max	158.0±2.8	159.2±4.3	157.9±2.9	158.3±3.0	$F_{(1,11)}=1.26$	0.285	0.103	0.177	
		Min	130.4±3.4	131.9±4.2	126.8±3.2	127.2±2.8	$F_{(1,11)}=1.13$	0.310	0.093	0.163	
		ROM	27.6±2.5	27.3±1.4	31.1±3.4	31.1±3.1	$F_{(1,11)}=0.20$	0.662	0.018	0.070	
Hip (°)	12	Max	143.6±7.3	145.2±7.4	147.0±7.7	149.0±7.7	$F_{(1,11)}=1.69$	0.220	0.133	0.221	
		Min	87.2±7.1	89.2±7.1	84.7±6.3	86.1±6.7	$F_{(1,11)}=1.34$	0.271	0.109	0.185	
		ROM	56.4±4.3	56.0±3.6	62.3±4.4	63.0±4.9	$F_{(1,11)}=0.02$	0.889	0.002	0.052	
Ankle (°)	12	Max	103.4 (100.3–106.7)	103.0 (101.1–104.8)	107.4 (106.3–110.5)	107.0 (105.9–108.1)					<0.001†
		Min	56.7±2.7	57.5±3.9	54.8±2.8	55.9±2.7	$F_{(1,11)}=1.26$	0.285	0.103	0.177	
		ROM	47.9±5.0	45.8±4.1	54.4±5.8	52.4±5.0	$F_{(1,11)}=9.74$	0.010*	0.470	0.810	
Hip-ankle distance (m)	12	Max	4.8±0.3	4.9±0.4	5.3±0.4	5.4±0.5	$F_{(1,11)}=4.72$	0.053	0.300	0.509	
		Min	−1.9±0.3	−2.0±0.3	−2.0±0.2	−2.0±0.3	$F_{(1,11)}=0.33$	0.579	0.029	0.082	
		ROM	6.7±0.6	6.9±0.6	7.3±0.5	7.4±0.6	$F_{(1,11)}=3.47$	0.089	0.240	0.398	
Cycle length (m)	12		3.1±0.4	3.3±0.6	3.9±0.4	4.1±0.8	$F_{(1,11)}=1.62$	0.229	0.128	0.214	
Cycle rate (Hz)	12		0.71±0.04	0.70±0.05	0.75±0.04	0.75±0.03	$F_{(1,11)}=0.15$	0.710	0.013	0.064	
Peak force (N)	11		1223.1±208.5	1198.2±155.8	1297.8±204.1	1212.7±180.4	$F_{(1,10)}=1.64$	0.229	0.141	0.213	
Average force (N)	11		408.9±60.6	391.4±54.8	412.0±75.1	349.9±51.6	$F_{(1,10)}=9.69$	0.011*	0.492	0.801	

Normally distributed data are presented as mean ± standard deviation while non-normally distributed data are presented as median (interquartile range)

TRAD traditional ski setting, *FMT* flow motion technology setting, *ES* ($_p\eta^2$) effect size (partial eta squared), *ROM* range of motion

*Significant main effect of ski setting, $p < 0.05$

†Significant Friedman test effect, $p < 0.001$

Table 2 Biomechanical responses to the two ski settings (TRAD and FMT) at the two sub-maximal exercise intensities (stages 1 and 2) during double poling

	N		Sub-maximal stage 1		Sub-maximal stage 2		Main effect for ski setting				Friedman test
			TRAD	FMT	TRAD	FMT	F ratio	p value	ES ($_p\eta^2$)	Power	
Ski-cradle (°)	11	Max	0.5 (0.3 to 0.6)	2.1 (1.9 to 2.5)	0.5 (0.3 to 0.6)	2.2 (2.0 to 2.4)					$<0.001^†$
		Min	−0.03 (−0.17 to 0.23)	−0.9 (−1.4 to −0.7)	−0.04 (−0.22 to 0.23)	−0.9 (−1.5 to −0.7)					$<0.001^†$
		ROM	0.4 (0.3 to 0.6)	3.4 (2.8 to 3.7)	0.5 (0.3 to 0.6)	3.1 (2.9 to 3.5)					$<0.001^†$
Knee (°)	12	Max	160.9±3.6	160.3±2.7	160.3±4.1	161.8±3.6	$F_{(1,11)}=0.45$	0.514	0.040	0.095	
		Min	133.4±5.1	133.3±5.2	130.6±5.8	130.6±3.7	$F_{(1,11)}<0.001$	0.991	<0.001	0.050	
		ROM	27.5±5.9	27.0±6.4	29.8±7.3	31.2±5.8	$F_{(1,11)}=0.19$	0.668	0.017	0.069	
Hip (°)	12	Max	127.2±7.8	128.6±7.6	127.9±8.6	130.9±8.2	$F_{(1,11)}=3.13$	0.105	0.222	0.365	
		Min	87.5±8.6	90.3±7.5	84.8±8.4	87.8±7.7	$F_{(1,11)}=4.84$	0.050	0.306	0.519	
		ROM**	39.7±5.7	38.3±5.5	43.1±5.6	43.1±6.3	$F_{(1,11)}=0.77$	0.399	0.066	0.127	
Ankle (°)	12	Max	83.4 (80.7 to 85.6)	81.6 (79.4 to 86.1)	84.6 (81.1 to 89.8)	85.4 (79.9 to 86.8)					0.532
		Min	67.5 (66.0 to 69.6)	69.1 (65.1 to 70.1)	68.0 (65.3 to 69.4)	68.3 (66.8 to 70.6)					0.440
		ROM	15.5±2.1	14.5±4.8	17.3±4.9	16.2±4.8	$F_{(1,11)}=2.66$	0.131	0.195	0.319	
Hip–ankle distance (m)	12	Max	0.7±0.2	0.8±0.3	0.7±0.4	0.9±0.3	$F_{(1,11)}=4.41$	0.060	0.286	0.483	
		Min	−2.0±0.4	−1.7±0.4	−2.2±0.5	−1.8±0.5	$F_{(1,11)}=12.91$	0.004*	0.540	0.904	
		ROM	2.7±0.5	2.5±0.4	2.9±0.4	2.7±0.4	$F_{(1,11)}=17.76$	0.001*	0.617	0.969	
Cycle length (m)	12		4.6±0.6	4.6±0.7	5.3±0.7	5.2±1.0	$F_{(1,11)}=0.30$	0.594	0.027	0.079	
Cycle rate (Hz)	12		0.77±0.06	0.77±0.07	0.82±0.08	0.82±0.08	$F_{(1,11)}=0.05$	0.820	0.005	0.055	
Peak force (N)	7		532.3±53.2	550.0±64.2	613.5±64.6	540.4±97.7	$F_{(1,6)}=0.51$	0.504	0.078	0.093	
Average force (N)	5		309.9±40.9	287.2±49.0	341.4±66.8	302.0±72.9	$F_{(1,4)}=0.46$	0.537	0.102	0.083	

Normally distributed data are presented as mean±standard deviation while non-normally distributed data are presented as median (interquartile range)

TRAD traditional ski setting, *FMT* flow motion technology setting, *ES* ($_p\eta^2$) effect size (partial eta squared), *ROM* range of motion

*Significant main effect of ski setting, $p<0.05$

**Significant interaction effect between ski setting and intensity, $p<0.05$

†Significant Friedman test effect, $p<0.001$

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Table 3 Biomechanical responses to the two ski settings (TRAD and FMT) during the 6-min self-paced time trial using diagonal stride and maximal velocity double-poling test

	N		TRAD	FMT	p value	ES (D_{rm})	Power
TT							
Ski-cradle (°)	8	Max	0.8 ± 0.3	2.7 ± 0.2	<0.001*	7.69	1.000
		Min	-0.3 ± 0.3	-2.0 ± 0.9	0.003*	2.45	0.974
		ROM	1.1 ± 0.5	4.7 ± 1.0	<0.001*	4.74	1.000
Knee (°)	12	Max	157.8 (155.7 to 159.1)	157.6 (156.7 to 159.5)	0.209		0.066
		Min	120.1 (120.1 to 125.4)	122.9 (121.4 to 124.6)	0.239		0.078
		ROM	33.8 (31.8 to 35.3)	34.4 (33.1 to 35.9)	0.937		0.105
Hip (°)	11	Max	147.9 ± 7.8	150.3 ± 6.9	0.065	0.32	0.626
		Min	81.4 ± 6.3	83.7 ± 6.1	0.157	0.37	0.282
		ROM	66.5 ± 4.6	66.7 ± 4.9	0.812	0.03	0.056
Ankle (°)	12	Max	109.7 ± 6.3	108.7 ± 5.5	0.223	0.16	0.219
		Min	53.2 (51.0 to 55.2)	54.8 (52.6 to 55.6)	0.272		0.050
		ROM	54.6 (51.7 to 59.4)	53.2 (50.9 to 56.2)	0.041*		0.092
Hip-ankle distance (m)	12	Max	4.9 ± 0.4	5.0 ± 0.4	0.104	0.32	0.367
		Min	-2.5 (-2.8 to -2.4)	-2.6 (-2.7 to -2.3)	0.136		0.192
		ROM	7.3 (7.0 to 7.9)	7.4 (7.1 to 7.7)	0.814		0.084
Cycle length (m)	12		3.7 ± 0.5	3.8 ± 0.5	0.223	0.19	0.219
Cycle rate (Hz)	12		0.84 ± 0.05	0.83 ± 0.04	0.656	0.10	0.071
V_{max}							
Cycle length (m)	12		4.8 ± 1.1	4.3 ± 1.1	0.050*	0.44	0.518
Cycle rate (Hz)	12		1.10 ± 0.12	1.22 ± 0.26	0.090	0.58	0.396

Normally distributed data are presented as mean ± standard deviation while non-normally distributed data are presented as median (interquartile range)

TRAD traditional ski setting, *FMT* flow motion technology setting, *ES (D_{rm})* effect size (Cohen's D for repeated measures), *TT* time trial, *V_{max}* maximum velocity test, *ROM* range of motion

*Significant difference between ski settings, $p < 0.05$

skiers [15]. With increased CL during sub-maximal diagonal stride, the absolute duration of the contralateral arm and leg recovery phase, and therefore, the duration of uninhibited blood perfusion and oxygen delivery, will increase [10]. This increased perfusion may potentially improve diagonal-stride efficiency. However, despite the trend, the results of this study showed no significant benefit of FMT on sub-maximal GE or TT performance with diagonal stride. A potential reason could be impaired balance associated with FMT. Speculatively, the significantly reduced sub-maximal diagonal-stride ankle ROM might have countered any instability, potentially also impairing plantar force production with FMT. Indeed, reduced ankle ROM and maximal ankle angle reduce the force production from the ankle plantar flexors during walking [33]. The force and power production of the ankle plantar flexors are important for both economy [33] and centre of mass forward acceleration [34] in walking and running, respectively. A similar impairment may, therefore, be present in cross-county skiing. These indications of impaired technique with FMT may explain the trend for increased sub-maximal $\dot{V}O_2$ with FMT.

With many skiers now utilising dynamic leg extension [35] associated with the 'kangaroo' double-poling style [18], the 'jump' duration in the double-poling preparation phase might be expected to increase with FMT due to the rocking motion. Increasing the preparation phase duration has been shown as the only variable able to predict double-poling V_{max} performance, with only faster skiers utilising the technique [11]. The preparation phase contributes to increased poling force production by increasing the centre of mass forward lean relative to the total foot support area and use of the skier's body mass in propulsion [13, 14]. Increased centre of mass ROM displacement has also predicted the reduced energetic cost of sub-maximal double poling in international versus regional skiers [12]. However, it seems that FMT offered no significant benefit to V_{max} performance or CL when using double poling. The significantly increased double-poling hip-to-ankle minimum distance indicates reduced forward lean of the hips in front of the ankles with FMT compared to TRAD, potentially suggesting a reduction in body-mass contribution to poling propulsion. Again, this may be due to impaired balance, with skiers reducing their centre of mass forward displacement (i.e., in front of the

Table 4 Physiological responses to the two ski settings (TRAD and FMT) at the two sub-maximal exercise intensities (stages 1 and 2) during diagonal stride and double poling

	N		Sub-maximal stage 1		Sub-maximal stage 2		Main effect for ski setting			Power	Friedman test
			TRAD	FMT	TRAD	FMT	F ratio	p value	ES ($_p\eta^2$)		
$\dot{V}O_2$ (L/min)	13	DS	2.70±0.55	2.78±0.53	3.70±0.78	3.77±0.78	$F(1,12)=3.98$	0.069	0.249	0.450	
		DP	2.48±0.51	2.61±0.62	3.17±0.74	3.21±0.76	$F(1,12)=3.14$	0.102	0.207	0.371	
$\dot{V}E$ (L/min)	13	DS	66.5±11.3	67.5±10.7	99.6±18.8	98.9±19.6	$F(1,12)=0.02$	0.894	0.002	0.052	
		DP	69.1±14.9	71.9±16.1	92.7±21.2	93.0±20.7	$F(1,12)=2.31$	0.155	0.161	0.287	
RER	13	DS	0.86±0.02	0.85±0.02	0.92±0.02	0.91±0.02	$F(1,12)=2.78$	0.121	0.188	0.335	
		DP	0.89±0.03	0.88±0.03	0.92±0.03	0.90±0.03	$F(1,12)=6.09$	0.030*	0.337	0.621	
HR (bpm)	13	DS	137±7	138±10	167±8	168±9	$F(1,11)=0.22$	0.650	0.019	0.071	
		DP	141±10	141±10	163±7	163±8	$F(1,11)=0.11$	0.743	0.010	0.061	
RPE	13	DS	11±2	11±2	14±1	14±1	$F(1,11)=0.04$	0.851	0.003	0.054	
		DP	12±2	12±2	15±1	14±1	$F(1,11)=0.03$	0.862	0.003	0.053	
GE (%)	13	DS	19.8 (19.5–20.0)	19.3 (18.5–19.7)	19.1 (18.2–19.3)	18.3 (17.7–19.1)					0.041[†]
		DP	17.2±1.8	16.5±1.4	16.4±1.1	16.3±1.3	$F(1,12)=3.27$	0.096	0.214	0.384	
BLa (mmol/L)	12	DS	–	–	–	–					
		DP	1.36±0.65	1.39±0.53	2.67±1.52	2.86±1.28	$F(1,11)=0.46$	0.512	0.040	0.095	

Normally distributed data are presented as mean±standard deviation, while non-normally distributed data are presented as median (interquartile range)

DS diagonal stride, *DP* double poling, $\dot{V}O_2$ oxygen consumption, $\dot{V}E$ ventilation, *RER* respiratory exchange ratio, *HR (bpm)* heart rate (beats per minute), *RPE* rate of perceived exertion, *GE* gross efficiency, *BLa* blood lactate, *TRAD* traditional ski setting, *FMT* flow motion technology, *ES ($_p\eta^2$)* effect size (partial eta squared)

*Significant main effect of ski setting, $p < 0.05$

[†]Significant Friedman test effect, $p < 0.05$

Table 5 Physiological responses to the two ski settings (TRAD and FMT) during the 6-min self-paced time trial. Normally distributed data are presented as mean ± standard deviation while non-normally distributed data are presented as median (interquartile range)

	N	TRAD	FMT	p value	ES (D_{rm})	Power
Average $\dot{V}O_2$ (L/min)	12	3.91 ± 0.72	4.08 ± 0.81	0.140	0.223	0.307
$\dot{V}O_{2peak}$ (L/min)	12	4.61 ± 0.85	4.71 ± 0.92	0.256	0.121	0.195
$\dot{V}O_{2peak}$ (mL/kg/min)	12	62.9 ± 6.0	64.2 ± 5.8	0.188	0.246	0.250
Average $\dot{V}E$ (L/min)	12	135.2 (118.8–145.8)	131.9 (111.0–154.7)	0.875		0.061
Average RER	12	0.99 ± 0.02	0.98 ± 0.03	0.178	0.435	0.259
Average HR (bpm)	11	177 ± 9	179 ± 11	0.089	0.158	0.398
Maximal HR (bpm)	11	189 ± 11	190 ± 11	0.014*	0.081	0.776
Peak BLa (mmol/L)	11	12.79 ± 1.80	12.28 ± 1.91	0.459	0.275	0.108

TRAD traditional ski setting, *FMT* flow motion technology, *ES (D_{rm})* effect size (Cohen's *D* for repeated measures), $\dot{V}O_2$ oxygen consumption, $\dot{V}O_{2peak}$ peak oxygen consumption, $\dot{V}E$ ventilation, *RER* respiratory exchange ratio, *HR (bpm)*, heart rate (beats per minute), *BLa* blood lactate

*Significant difference between ski settings, $p < 0.05$

foot support area) with FMT, to maintain stability. Reduced balance and limited use of the preparation phase may therefore reduce the efficiency and increase the energetic cost of double poling [12]. The trends for reduced sub-maximal GE and increased sub-maximal $\dot{V}O_2$ during double poling with FMT support this notion. Aside from this, there were few other significant perturbations to the physiological responses with FMT.

There were limitations in the current study that should be considered. First, some significant differences between conditions were small and may be susceptible to measurement or type 1 errors. For example, the significant increase in maximal HR (by 1 bpm) with FMT was within the range previously cited for the difference between the HR monitor and ECG [27]. Furthermore, there was a significant order effect of TT performance, whereby distance covered was significantly reduced during the second trial (1074 ± 99 m) compared to the first (1096 ± 104 m; $p = 0.009$). This is likely due to fatigue or reduced motivation after the first trial; however, the counter-balanced randomisation of starting condition will have prevented bias. The statistical power of the study was relatively low, and the chance of a type 2 error was high in some of the tests completed, due to participant exclusion with missing values. The results suggest that lack of balance may have influenced performance with FMT. While speculative, it is possible that different interactions between FMT and treadmill roller skiing may have led to greater disruptions in stability compared to TRAD. Therefore, despite familiarisation with the technology before experimental trials, more extensive treadmill roller skiing practice might have been beneficial. It also remains unknown whether the observed differences with FMT compared to TRAD would be consistent over repeated trials. Using statistical methods similar to those reported previously [36], test–retest reliability with FMT could be assessed in future to determine the repeatability of the measured variables.

5 Conclusion

No clear benefit of FMT on roller-skiing performance has been demonstrated in this cohort of well-trained cross-country skiers when using diagonal stride or double poling. These findings are important to consider when developing FMT roller-ski products in the future, as well as in the further study of cross-country skiing with FMT in laboratory and field settings. It is recommended that athletes spend extended periods of time familiarising with FMT in future studies before the technology is compared with a traditional control, to perhaps reduce the impact of FMT on balance and technique. In addition, the effectiveness of FMT on snow remains to be explored.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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