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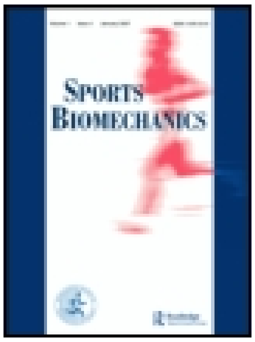

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Push-off forces in elite short-track speed skating

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ABSTRACT

This study performed an analysis of the push-off forces of elite-short-track speed skaters using a new designed instrumented short-track speed skate with the aim to improve short-track skating performance. Four different skating strokes were distinguished for short-track speed skaters at speed. The strokes differed in stroke time, force level in both normal and lateral directions, and the centre of pressure (COP) on the blade. Within the homogeneous group of male elite speed skaters ($N = 6$), diversity of execution of the force patterns in the four phases of skating was evident, while skating at the same velocities. The male participants ($N = 6$) with a better personal record (PR) kept the COP more to the rear of their blades while hanging into the curve ($r = 0.82$, $p < 0.05$), leaving the curve ($r = 0.86$, $p < 0.05$), and entering the straight ($r = 0.76$, $p < 0.10$). Furthermore, the male skaters with a better PR showed a trend of a lower lateral peak force while entering the curve ($r = 0.74$, $p < 0.10$). Females showed a trend towards applying higher body weight normalised lateral forces than the males, while skating at imposed lower velocities.

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Engineering; performance; force measurement; techniques

Introduction

Short-track speed skating is a form of competitive ice speed skating where multiple skaters compete on a short (111 m) oval ice track. Skaters ride the curves of this oval at very high velocities, challenging the high centrifugal forces. Applying the right skating technique is crucial to pass these curves and maintain position in the group during a match. However, little is known on the biomechanical background of the short-track skating technique. It is therefore unclear what the ideal technique is and therefore also what to correct for in athlete skaters.

Although biomechanical research on short-track speed skating is limited, there has been much research done on the technique of long-track speed skating. However, the technique of long-track speed skating significantly differs from that in short-track. In the long-track discipline skaters make six to eight symmetric strokes at the straight part, before entering

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the curve, whereas short-track speed skating is mainly skating curves. Since the curves in long-track speed skating are wider, and the skaters wear klapskates instead of fixed skates, also these techniques differ from the short-track discipline.

The motion of a short-tracker at speed can be divided into four phases: entering the curve (EC), hanging into the curve (C), leaving the curve (LC) and entering the straight (ES). Apart from which skating technique, it is also not clear which phase is most critical for performance. These issues could be addressed by measuring the push-off forces of a skater. For short-track, there are no data available yet on the force patterns or force levels applied during skating for these four phases.

In long-track speed skating, an instrumented klapskate has been developed, measuring the push-off forces in normal and lateral direction and determining the centre of pressure (COP) on the blade (Houdijk, de Koning, de Groot, Bobbert, & van Ingen Schenau, 2000; van der Kruk, den Braver, Schwab, van der Helm, & Veeger, 2016; Yuki, Ae, & Fujii, 1996). Different from the hinge-opening klapskate in long-track, in short-track skaters have a fixed blade, where the shoe is placed off-centre from the blade. An instrumented skate should enable a skater to wear her own shoes and ride her own blade.

The purpose of this paper is to perform an analysis of the push-off forces of elite-short-track speed skaters, to eventually improve the short-track skating performance. First, we report on an instrumented short-track speed skate; Secondly, a general description of the force patterns in short-track speed skating in terms of stroke-time, normal and lateral force level and COP on the blade is given, based on force data of elite speed skaters. Thirdly, we explore within-group differences in a group of elite speed skaters related to their ranking based on personal records (PR). We hypothesise that, despite the homogeneity of a group of elite short-trackers, the instrumented skate can determine differences in push-off techniques within the group.

Method

Data collection

Data were collected on an indoor ice rink in Thialf Heerenveen. Twelve (eight male and four female) Dutch elite short-track skaters participated in the experiment after signing a written informed consent, which had been approved by the Delft University of Technology Human Research Ethics Committee. All riders were within the top 70 of the world ranking (WR). However, two males were excluded from the test, since one fell and one did not perform according to exercise, and one female was excluded due to failing equipment. All riders were equipped with an instrumented skate at their right foot which measured the normal and lateral forces at the skate and the point of application of the force (COP) (Figure 1). Force measurements were only performed for one side, due to the available means. In consultation with the national coach, the right side was chosen, it being the most interesting side during the curve. The skaters were filmed by five cameras, one at each end of the straight, one at the inside of each curve and one panning camera at the finish line. The skaters skated five rounds at constant velocity. The participants were asked to skate lap times of 9.2 s to 9.3 s for the males, and 9.8–9.9 s for the females. Lap times were measured with a transponder worn by the skaters, using the MyLaps system (MYLAPS Timing Services, Nijmegen, the Netherlands).

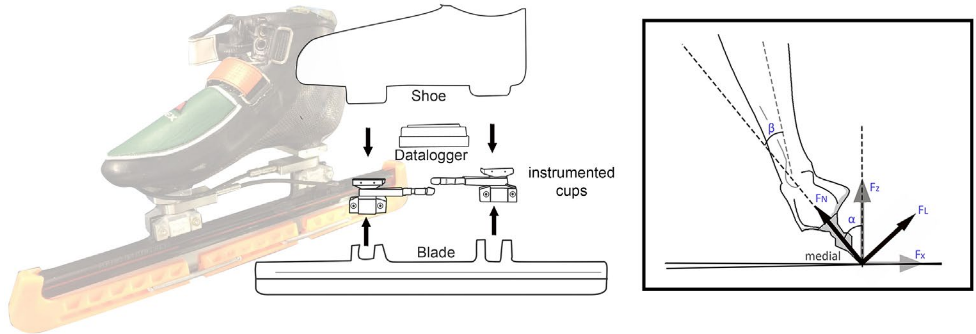

Figure 1. The ISTS consists of two self-designed cups (mountable on EVO blades).
The skate measures the forces in the normal (Fn) and lateral (Fl) direction of the blade. The lean angle of the skate (α) distributes these local forces into the horizontal push-off force (Fh) and the vertical force (Fv). Due to eversion of the foot (β), there can be a skewed push-off on the skate.

The skaters were ranked based on their PR in an *XL* (an all-out lap when the skater is at speed) during practice, which was obtained via the national coach. The average PRs and measured lap times with the corresponding SDs are given in Table 1.

Instrumented short-track skate

The instrumented short-track skate (ISTS) consists of two self-designed cups (mountable on high-end blades of the brand EVO) (Figure 1). Each cup consists of a sandwich construction that clasps a piezoelectric three-component force sensor (Kistler 9602, Kistler Group, Winterthur, Switzerland). The output of the sensor is logged on a SD card and sent over Bluetooth via a data logger (Shimmer3, Ireland). The force sensors are powered by rechargeable Li-Ion batteries. A digital start–end pulse can be logged, to enable synchronisation with external measurement devices. The weight of the instrumented cups and electronics is 400 g. The instrumented cups replace the normal cups of the skate, so in total the added weight is 340 g (around 25% of the total skate). The height of the instrumented cups is 18 mm (normal height differs among skaters, on average 12 mm).

The calibration of the ISTS was performed using a tensile testing machine (Zwick Z100, Zwick Roell, Ulm, Germany, principal accuracy 1 N). The set-up is the same as the one used in van der Kruk et al., (2016), with the single difference that not four, but five positions (P1-P5) were tested on the blade (applied force up to 2,500 N). Calibration in normal direction resulted in correlations of R^2 = 0.989, with a root-mean-square error (RMS) of 55 N (SEM = 1 N); the correlation for the lateral direction yielded R^2 = 0.993 with the corresponding RMS error of 23 N (SEM = 0.4 N). As the force in longitudinal direction (ice friction) is likely to be lower than 10 N (Lozowski, Szilder, & Maw, 2013), which is lower than the cross-talk of the sensors, this force component is not used.

Data analysis

Push-off forces (force patterns)

The measured forces were divided into separate strokes over the four phases: entering the curve (EC), hanging into the curve (C), leaving the curve (LC) and entering the straight

Table 1. (A, B) M ± SD of the PRs and Laptimes, and the average and peak measured normal and lateral forces (normalised to body weight), COP at the blade, and Stroke Time. For stroke EC, C, and LC five strokes ($s = 5$) per participant were included, for stroke ES three ($s = 3$). (B) males and females separately.

				[A]		[B]			
				$N = 9$ (males and females)		$N = 3$ (females)		$N = 6$ (males)	
				Avg	Peak	Avg	Peak	Avg	Peak
PR			(s)	8.3 ± 0.22		8.50 ± 0.16		8.1 ± 0.08	
Laptimes		*s*	(s)	9.49 ± 0.37		9.95 ± 0.19		9.26 ± 0.10	
Normal force	EC	5	(N/BW)	0.96 ± 0.10	1.66 ± 0.15	1.05 ± 0.12	1.78 ± 0.17	0.92 ± 0.06	1.60 ± 0.10
	C	5	(N/BW)	1.40 ± 0.17	1.96 ± 0.16	1.30 ± 0.24	2.01 ± 0.21	1.45 ± 0.14	1.94 ± 0.15
	LC	5	(N/BW)	1.02 ± 0.09	1.55 ± 0.16	0.99 ± 0.12	1.56 ± 0.14	1.04 ± 0.08	1.55 ± 0.18
	ES	3	(N/BW)	0.88 ± 0.06	1.32 ± 0.10	0.88 ± 0.11	1.38 ± 0.14	0.88 ± 0.03	1.29 ± 0.08
Lateral force	EC	5	(N/BW)	0.24 ± 0.08	0.77 ± 0.22	0.32 ± 0.03	1.00 ± 0.14	0.19 ± 0.07	0.66 ± 0.16
	C	5	(N/BW)	0.41 ± 0.08	0.74 ± 0.23	0.48 ± 0.06	1.02 ± 0.10	0.37 ± 0.06	0.59 ± 0.09
	LC	5	(N/BW)	0.31 ± 0.07	0.75 ± 0.19	0.38 ± 0.05	0.97 ± 0.12	0.27 ± 0.04	0.64 ± 0.08
	ES	3	(N/BW)	0.28 ± 0.08	0.66 ± 0.24	0.35 ± 0.05	0.91 ± 0.21	0.24 ± 0.07	0.53 ± 0.12
COP	EC	5	(–)	0.45 ± 0.03	0.83 ± 0.14	0.46 ± 0.01	0.91 ± 0.10	0.44 ± 0.03	0.79 ± 0.15
	C	5	(–)	0.49 ± 0.03	0.88 ± 0.10	0.50 ± 0.02	0.98 ± 0.02	0.49 ± 0.03	0.83 ± 0.08
	LC	5	(–)	0.48 ± 0.03	0.79 ± 0.11	0.48 ± 0.01	0.77 ± 0.09	0.48 ± 0.03	0.80 ± 0.13
	ES	3	(–)	0.44 ± 0.04	0.55 ± 0.05	0.44 ± 0.03	0.57 ± 0.07	0.44 ± 0.04	0.54 ± 0.04
Stroke time	EC	5	(s)	1.12 ± 0.17		1.22 ± 0.17		1.07 ± 0.15	
	C	5	(s)	0.99 ± 0.14		0.92 ± 0.09		1.02 ± 0.16	
	LC	5	(s)	0.61 ± 0.08		0.68 ± 0.09		0.57 ± 0.04	
	ES	3	(s)	0.65 ± 0.08		0.73 ± 0.05		0.61 ± 0.06	

(ES). All measured force data were normalised to body weight. The M and SD of the peak (*peak*) and average (*avg*) normal (F_N) and lateral forces (F_L), the COP on the blade, and the stroke-time (ST) of nine participants (six males, three females) were determined. Of each participant five strokes ($s = 5$) were included for EC, C and LC and three strokes of ES ($s = 3$), because fewer strokes were available since sometimes a short, corrective stroke was performed instead of ES. We will refer to this corrective stroke as a transition stroke (*T*). Since this stroke is only performed sporadically, we did not include the stroke in the statistical analysis.

A repeated measures ANOVA ($N = 9$) was performed to compare phases (EC, C, LC, ES) for the within-participants variables: $F_{N\text{-peak}}$, $F_{N\text{-avg}}$, $F_{L\text{-peak}}$, $F_{L\text{-avg}}$, COP_{peak}, COP_{avg}, ST; sex was added as a between-participant factor. Only for the average normal force ($F_{N\text{-avg}}$) an interaction effect between sex and stroke phases was found, however since the effects for average normal force within men and women were similar, it is justifiable to still take the groups together and look at the main effect. Pairwise comparison was done with a Bonferroni *post hoc* analysis when a main effect was found. Only for stroke time (ST) sphericity was not met, for which a Greenhouse–Geisser correction was performed. A significance level of $p < 0.05$ was employed.

Within-group differences and PR

To determine the correlation between PR and the *average,* and *peak forces* in *normal,* and *lateral* direction, a *Pearson* test was performed resulting in a pairwise linear correlation coefficient (*r*). Additionally, the correlation between PR and the average *COP on the blade* was tested. These analyses were performed on the males only ($N = 6$), due to the small sample size of the female group. From each participant, the peak and average push-off forces were determined for each measured stroke; the average was taken over the measured strokes to enter as number in the Pearson test. A significance level of $p < 0.05$ was employed, $p < 0.10$ was used for comparisons which are close to be significant.

Results

Instrumented skate

The instrumented skate functioned well during the testing and the signals of the skate were stable throughout the experiment. Installing and de-installing the instrumented pots on the skater's shoe and blade was done on the ice in less than five minutes by the equipment manager of the team. In spite of the increased height and weight of the skate, the skaters felt comfortable riding the skate at high velocities.

Push-off forces

A main effect was found between the different phases for the variables $F_{N\text{-peak}}$, $F_{N\text{-avg}}$, $F_{L\text{-avg}}$, COP_{peak}, COP_{avg}, and ST (Table 1). Based on the pairwise comparison (Table 2), the four different phases (EC, C, LC, ES) could be distinguished based on the normal and lateral force level of the push-off forces of the skaters). Figure 2 and Figure 3 show the skating motion together with the measured normal and lateral forces and COP (averaged over nine participants).

Table 2. Repeated measures one-way Anova of the phases EC, C, LC and ES for the nine participants.

N = 9								
Avg	*F*-test	Mauchly's sphericity	Bonferroni					
			EC-C	EC-LC	EC-ES	C-LC	C-ES	LC-ES
Normal force	$F(3,21) = 81.92$, $p < 0.001$	$\chi^2(5) = 7.66$, $p = 0.180$	x		x	x	x	x
Lateral force	$F(3,21) = 34.47$, $p < 0.001$	$\chi^2(5) = 9.024$, $p = 0.100$	x	x		x	x	
COP	$F(3,21) = 16.62$, $p < 0.001$	$\chi^2(5) = 4.002$, $p = 0.550$	x	x			x	x
Stroke time	$F(1.35,9.43) = 32.77$, $p = 0.0001$	$\chi^2(5) = 16.01$, $p = 0.010$*	x	x	x	x		
Peak								
Normal Force	$F(3,21) = 68.10$, $p < 0.001$	$\chi^2(5) = 8.099$, $p = 0.110$	x		x	x	x	x
Lateral Force	$F(3,21) = 2.31$, $p = 0.105$	$\chi^2(5) = 6.093$, $p = 0.230$						
COP	$F(3,21) = 29.60$, $p < 0.001$	$\chi^2(5) = 8.020$, $p = 0.150$			x	x	x	x

Notes: Pairwise comparison of the different motion phases (EC, C, LC, ES) is performed using a Bonferroni *post hoc* analysis; *x* indicates a significant difference ($p < 0.05$).
*sphericity is not met, a Greenhouse–Geisser correction was performed.

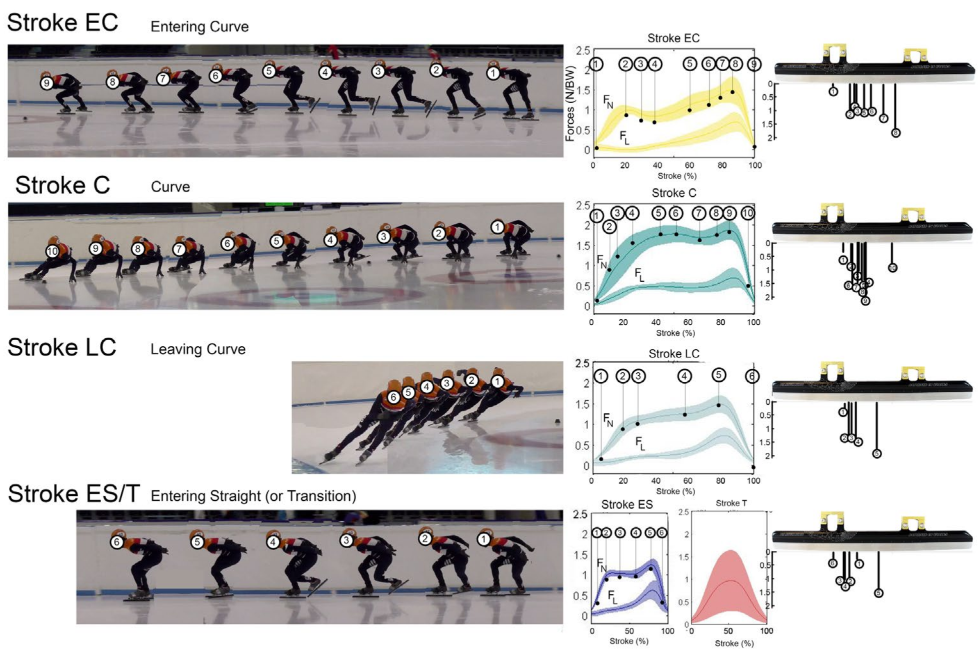

Figure 2. Overview of the short-track speed skating motion, measured at constant velocity.
Four strokes were distinguished, which are described in the results. The numbers indicated in the pictures correspond to the numbers in the graphs. Plotted are the mean measured normal and lateral forces of the six males and three females, the bandwidth indicates the SD. The strokes are normalised to time. The numbers at the blades indicate the COP at the blade in that instant of the stroke.

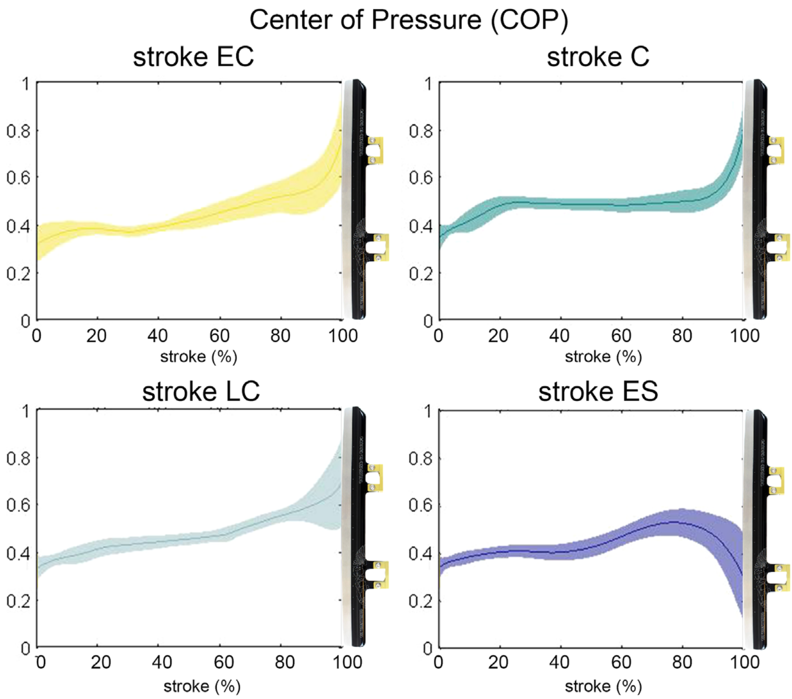

Figure 3. Plotted are the mean average positions of the COP throughout a stroke of the six males and three females; of each participant 5 strokes were included in the data.
The bandwidth is the SD. The strokes are normalised to time. The COP at the skate is indicated as a ratio, where 0 is at the rear of the blade and 1 is at the front of the blade. Remarkable is that in the stroke in which the skater enters the straight (ES), the COP shifts to the rear of the skate at the end of the stroke.

The strokes at the start of the curve (EC and C) are significantly longer than the other two strokes (ST = 1.12 s and ST = 0.99 s respectively). EC, the stroke in which the skater enters the curve, distinguished itself by the dip in normal force after the double stance phase (20–50% of the stroke) (Figure 2). Additionally, stroke EC was characterised by the highest peak normal forces (1.66 N/BW) (together with stroke LC (1.55 N/BW)), and the lowest average lateral force, (0.24 N/BW) (together with stroke ES (0.28 N/BW), with a mean peak lateral force of 0.77 N/BW.

Stroke C, the stroke where the skater hangs into the curve (see Figure 2) could be separated from the other three based on force profiles based on the high normal forces (average 1.40 N/BW, peak 1.96 N/BW) combined with the plateau-like lateral forces (average 0.41 N/BW, peak 0.74 N/BW).

The strokes where the skater exits the curve, stroke LC and ES, were significantly shorter than the other two (on average 0.61 s and 0.65 s, respectively). The first stroke leaving the curve (stroke LC) was characterised by significantly higher average and peak normal forces (1.02 N/BW and 1.55 N/BW, respectively) than the consecutive stroke, entering the straight (stroke ES) (0.88 N/BW and 1.32 N/BW, respectively). The COP of ES differed significantly from the other strokes: it shifted to the rear of the blade at the end of the motion —resulting in a peak COP of 0.55—, while in the other strokes, the skater moved to the front of the blade—resulting in a peak COP of 0.79–0.88.

The males were able to skate the specified lap time, while the females had a larger variation in maintaining their specified lap time. In Table 1(B), the measured data for males and females are given separately. The lap times of the females were higher than lap times of the males, as instructed. Note however that, although there is a large difference in lap times between the males and females, there is no difference in normal forces. The lateral forces per body weight of the females, however, show a clear trend to be higher compared to the males. Ranking the lateral forces for all participants shows that the females have the highest $F_{\text{L-peak}}$ for EC, C, and LC, and the highest $F_{\text{L-avg}}$ for LC. For the other phases, the females were in the fourth highest $F_{\text{L-peak}}$ and $F_{\text{L-avg}}$.

Correlation between measured force data and PR

The Pearson correlation—performed on the group of males to determine the correlation between PR and lateral force, normal force, and COP at constant speed—showed significant correlations between the COP and PR (Table 3, Figure 4). The average COP in LC and the peak COP in stroke C have a significant positive correlation ($r = 0.86$, $p = 0.030$ and $r = 0.82$, $p = 0.048$, respectively) with PR, indicating that skaters with a better PR keep their COP more to the rear of their blade when riding and exiting the curve. Also, the average COP in the curve and while entering the straight appears to show a positive relationship with PR ($r = 0.81$, $p = 0.052$ and $r = 0.76$, $p = 0.077$ respectively). Additionally, we found a positive trend ($r = 0.74$, $p = 0.096$) between PR and the peak lateral force in stroke EC, indicating that skaters with a better PR tend to apply lower lateral forces.

Although skating at similar speeds, the applied normal force levels (F_N) differed between the skaters. Figure 5 shows the most distinct force patterns between male individual speed skaters. The graphs show diversity between the elite male speed skaters in the executions of the four strokes, but this diversity could, in this study, not be related to PR with the chosen measures.

Discussion and implications

The practical usability of the developed ISTS was demonstrated in this experiment. The four phases (EC, C, LC, ES) in the short-track round could be well distinguished based on the measured push-off forces. Within the elite speed skaters, we determined differences in skating technique and related these to the ranking of the skaters based on PR, which led to significant correlations with COP and the lateral forces. This makes the instrumented skate

Table 3. Pearson correlation coefficient between PR and the forces, COP, and ST, of the males ($N = 6$).

		EC	C	LC	ES
Fn	Avg	0.72	0.57	−0.01	−0.01
	Peak	0.66	0.40	−0.14	0.18
Fl	Avg	0.63	0.69	0.73	0.62
	Peak	*0.74***	0.55	0.48	0.48
COP	Avg	0.60	*0.81***	**0.86***	*0.76***
	Peak	0.43	**0.82***	0.52	0.45
ST	Avg	−0.62	0.52	0.34	−0.40

*indicates a correlation where $p < 0.05$; **indicates a correlation where $p < 0.10$.

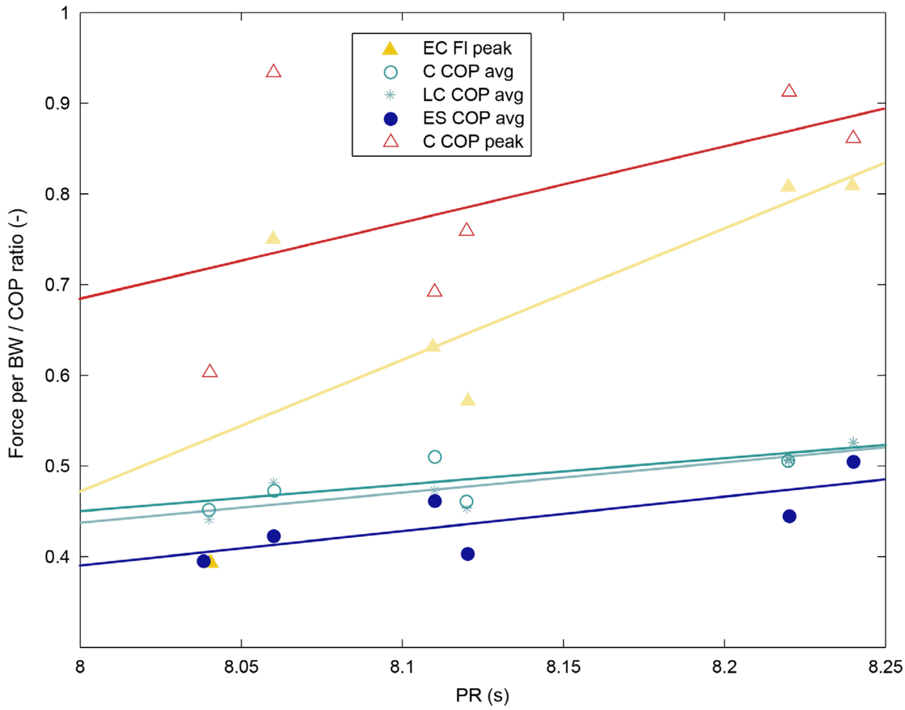

Figure 4. Scatterplot for the trends and correlations between PR and the normalised lateral forces, and COP position on the blade for the male participants ($N = 6$).

a useful tool for skaters and coaches during short-track practices. Despite the homogeneity of the group of elite short-trackers, the instrumented skate was able to determine differences in push-off techniques within the group.

Force patterns

The four phases in short-track speed skating can be distinguished with the instrumented skate based on force level, stroke time and the COP measured with the instrumented skate for the right side. The phase entering the curve, EC, distinguished itself by the dip in normal force after the double stance phase (20–50% of the stroke) (Figure 2). This is caused by the so-called *shuffle*, a motion where the skater changes from the medial (inside) to the lateral (outside) side of the blade and back. In this motion, skaters move their upper body up and down, which shifts the centre of mass of the skater, hence the dip in the normal force. Due to this shuffle, there is also a negative lateral force at the start of the stroke and the COP at the blade shifts from front to rear and back again. Stroke EC is also the only stroke where the skaters do not perform a cross-over with the left leg.

The force data of stroke C, where the skater leans into the curve, are most distinguishable from the other three by the high normal forces. The level of the normal force is here directly related to the centrifugal forces acting on the skater in the curve; these increase with an increased velocity. The decrease in normal force—just before the peak at the end of the stroke—is caused by the left (repositioning) leg in the air; this left leg is pulled to the front,

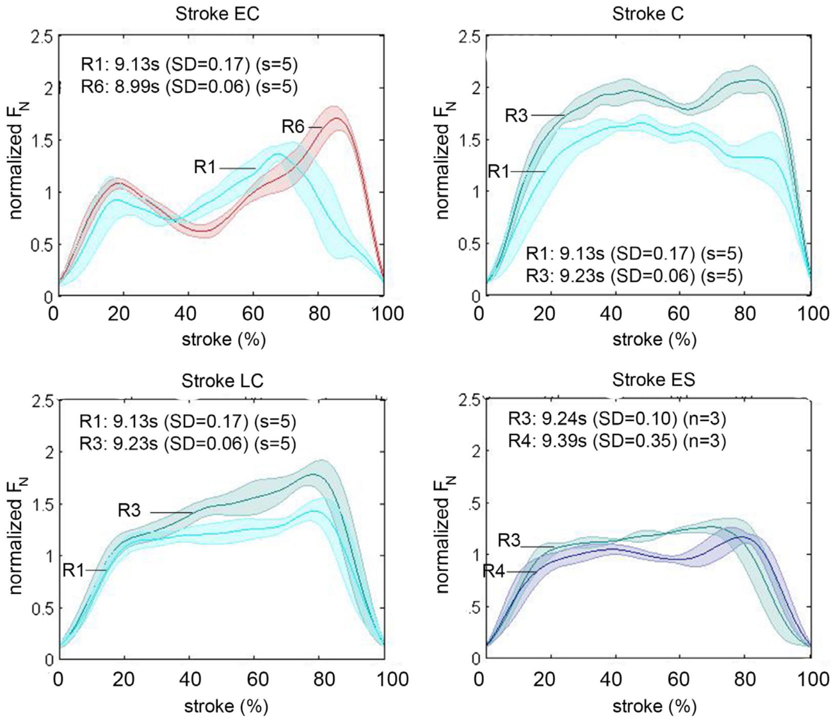

Figure 5. Most distinctive patterns between individual male skaters based on their normal force patterns. The shaded areas reflect one SD. The ranking of the skaters is indicating with R# (ranking 1–6, based on PR). The differences in normal force levels ($F_{N\text{-avg}}$, $F_{N\text{-peak}}$) between the skaters were *not related* to PR ranking. They probably have their origin in the efficiency of the skating motion.

thereby drawing it underneath the right leg, shifting the COM (Figure 2). This shifting in COM is what induces the decrease in the measured forces.

The COP of ES differs significantly from the other strokes: it shifts to the rear of the blade at the end of the motion, while in the other strokes, the skater moves to the front of the blade. This is caused by the fact that ES is a transitional stroke from the curve to the straight. The skater comes back upright, so most correction and steering is done here, which is linked to the COP on the blade.

In this study, only the forces on the right skate were measured. The comparison of average normal forces between skaters should therefore be interpreted with care, since the force on the left skate—during double stance, when both skates are on the ice—influences this force level. For a complete picture, it would therefore be beneficial to measure the push-off forces of both skates synchronously, also because, based on the knowledge of long-track speed skating, different force patterns are expected between left and right, especially for the forces in the curve (van der Kruk et al., 2016).

COP and lateral forces on the blade

Results show that the male skaters with a better PR kept the COP more to the rear of their blades while leaning into (C) and leaving (LC) the curve, and entering the straight (ES). Additionally, we found that skaters with a better PR, showed lower lateral peak forces while entering the straight. Although these results are based on a small sample size of elite speed skaters ($n = 6$), and may therefore not be as robust, it does seem to indicate that the *handling* of the skate is an important factor for short-track performance. We refer to *handling* as the actions to steer the skate. We expect that the skaters use the shifting of COP on the blade to steer, but also the lateral forces on the skate can be an intended action to induce a moment on the cups and thereby bending the blade, which will cause the skate to steer as well. The length and the stiffness of the blade then determine the necessary absolute lateral force level to bend it. Since the men and women skate on the same blade, and therefore likely need to apply the same absolute lateral forces, this might explain the fact that we found significant higher lateral forces when we corrected for body weight for the women.

Although not investigated yet, we hypothesise that this lateral force is, apart from the active steering control action of the skater, partly a result of an involuntary skewed push-off, due to a lack of active control to stabilise the knee and ankle. Felser et al. (2016) already found that the right ankle eversion's isometric and concentric maximum voluntary torque were significantly correlated to performance in short-track speed skating. A previous study in long-track speed skating already argued that a lateral force—in the frame of the skate—does not directly contribute to the forward velocity (performance) of the skater (van der Kruk, van der Helm, Schwab, & Veeger, 2016). Therefore, from a mechanical point of view, the lateral force should be minimised if it does not serve the purpose of steering the skate. Hence, the relation between active control to stabilise the knee and ankle and lateral force on the ice is a topic well worth looking into. Especially, since the female short-track skaters showed a trend of applying higher lateral forces per body weight than their male colleagues, while they skated on a—imposed—lower velocity.

Force level and performance

Although all male participants skated at the same velocities, and the four general stroke patterns could be distinguished, we do see diversity between elite male speed skaters in the executions of the four strokes. The normal force levels (F_N) differed between skaters at the same speed (Figure 5), but were not related to their ranking in PR. Since the skaters skated at the same velocities, differences in normal force levels seem to point at a difference in efficiency. Also, the fact that the female participants skated at lower velocities than the men, but did not apply lower normal forces (corrected to body weight), hangs towards an efficiency measure. To gain insight into this effect, data of individual skaters at different velocities and preferably some full-out exercises would be necessary. Also, measuring the velocity of separate strokes would be helpful. Expanding the number of participants would not only be hard—because the study is focused on top-level athletes—, but also doubtful whether it would benefit the results. It would certainly increase the robustness, but also decrease the sensitivity of an already homogeneous data-set with small margins. In the future, the instrumented skate and push-off force profiles can be used to determine the efficiency of elite short-track skaters and help to give training advice whether the skater should focus on improving strength or technique.

Conclusion

A wireless force measuring instrumented short-track speed skate was constructed and calibrated on a tensile testing machine (accurate up to 2.2% in normal direction and 1.4% in lateral direction), which could be used in routine training. Within the homogeneous group of male elite speed skaters, diversity of execution of the force patterns in the four phases of skating is evident, while skating at the same velocities. Higher ranked male skaters show a trend to have a COP more to the rear of the blade, and lower lateral forces for several phases. Females showed a trend towards applying higher body weight normalised lateral forces than the males, while skating at imposed lower velocities.

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