

Impact of Different Ground Surfaces and Gradient Conditions on the Spatio-Temporal Characteristics of the Bobsleigh Push Phase

Yan Liu

Shanghai University of Sport

Binghong Gao

Macao Polytechnic University

Xiaoqing Ding

Shanghai University of Sport

Min Gong

Guangzhou Sport University

Lijuan Mao

maolijuan@sus.edu.cn

Shanghai University of Sport

Research Article

Keywords: Bobsleigh, Push phase, Ground surfaces, Gait cycle parameters, COM motion parameters

Posted Date: August 14th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10566454/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at BMC Sports Science, Medicine and Rehabilitation on October 13th, 2026. See the published version at <https://doi.org/10.1186/s13102-026-02145-2>.

Abstract

Background

This study investigated whether ground surface and slope influence the push technique in bobsleigh on land versus ice.

Methods

Spatio-temporal parameters were collected from active national team bobsleigh athletes during land-based and ice-based pushing across the start, acceleration, and high-velocity phases using a markerless three-dimensional motion capture system. Bayesian independent-samples t-tests and paired-samples t-tests were used to compare parameters across positions and phases.

Results

The results showed that, in spatio-temporal gait parameters, the main differences across the pilot, pusher, and brakeman were a higher step frequency and shorter stride duration, stance time, swing time, and flight time on ice, with the start phase showing the largest proportion of differences across all positions. For centre-of-mass (COM) motion, vertical COM displacement (both maximum and mean) was smaller on ice across all positions. Mean and maximum horizontal COM velocities were generally greater on ice than on land. Mean acceleration was greater on ice during the start and acceleration phases but smaller during the high-velocity phase. Maximum acceleration was greater on ice during the start phase but generally smaller during the acceleration and high-velocity phases. The unique ice surface altered the athletes' spatio-temporal push performance, with the lower-limb push pattern adapting accordingly on ice.

Conclusions

Land-based training for the start and acceleration phases may carry a risk of negative transfer to ice pushing, while high-velocity phase training on land may fail to provide the sport-specific stimulus required for ice pushing. Based on these findings, it is recommended that land-based push training emphasise horizontal force application, moderately increase load to enhance step frequency and propulsive force, incorporate overspeed running and downhill push drills to strengthen neuromuscular control during the high-velocity phase, and include additional lower-limb eccentric and plyometric training.

Background

The final result in bobsleigh competition is determined by the total run time from the 15 m mark to the finish, with the fastest time winning. This total time comprises the push phase and the subsequent glide phase. During the push phase, the crew must accelerate the sled from rest, providing the sole source of propulsive energy before the sled enters the glide. Unlike other ice sports, bobsleigh and skeleton require athletes to wear spiked ice shoes and perform a loaded sprint during the push phase. This unique sprinting environment, together with the sport-specific demands, induces adaptive changes in the athletes' movement patterns.

Previous research on bobsleigh and skeleton has consistently shown that higher speed and shorter time during the start phase are advantageous for final performance [1–5]. Furthermore, higher-level athletes exhibit a more stable relationship between push time and overall race time. As sliding technique becomes increasingly refined, developing the athletes' push capability emerges as a key pathway to achieving superior competitive outcomes [6]. Thus, high performance during the push phase is a critical factor for success in bobsleigh.

Over the course of a season, training for the push phase is generally divided into land-based training in summer and ice-based training in winter. Land-based push training is typically performed individually on a standard synthetic track. This format offers high flexibility in training venue selection. Athletes wear sprint spikes and complete a 30-m push effort. The load applied to the sled simulates the average per-person weight during team pushing in competition, and can be adjusted according to different training objectives. Ice-based push training takes place on a track made entirely of ice, primarily in a team format to simulate actual competition scenarios. Athletes wear spiked ice shoes during training, and depending on position, the pushing distance increases from the pilot to the push athlete to the brakeman, with the shortest distance exceeding 20 m.

The most significant difference between land-based and ice-based pushing lies in the surface characteristics. On a synthetic track, high friction and high resilience are generally pursued to generate greater propulsive force, effective energy absorption and feedback, all of which facilitate running. In contrast, ice surfaces exhibit a lower coefficient of friction due to the lubrication of a liquid water film and a transition layer composed of ice crystals and liquid water [7]; ice hardness increases as temperature decreases, resulting in lower resistance on harder ice [8][9]. While conventional ice sports seek low friction for rapid gliding, bobsleigh requires the sled to move as smoothly as possible on ice to reduce

push resistance and increase gliding speed [10], while simultaneously demanding greater friction between the spiked shoes and the ice to effectively utilise ground reaction forces [11]. These conflicting demands make biomechanical analysis of bobsleigh particularly complex.

Studies on different sports surfaces have compared conditions such as synthetic tracks, concrete or asphalt, grass, and sand [12], as well as the effects of adjustable surface hardness on running kinematics, kinetics, and energy metabolism [13–16]. Among spatio-temporal parameters, no significant differences in ground contact time were found between harder surfaces and synthetic tracks, though contact time tended to be slightly longer on harder surfaces [12]. However, surfaces with markedly different hardness produced significant differences in contact time, step length, step frequency, and duty factor [14].

Apart from differences in friction and hardness, land-based and ice-based pushing also differ in gradient during the late acceleration and high-velocity phases. The push phase of the bobsleigh track is 65 m in length, with a 2% gradient for the first 15 m and 12% for the remaining section [17]. Therefore, during ice-based pushing, athletes must sprint and maintain acceleration and maximal speed on a smooth, hard ice surface with a substantial downhill gradient. In contrast, land-based training is conducted on a flat surface because of the absence of specialised push tracks for summer training, and thus involves no gradient. Current research on different gradients has mainly compared uphill and level running, whereas downhill running has received comparatively less attention, with running speeds typically set at moderate-intensity jogging [18]. Studies examining spatiotemporal parameters under various downhill gradients have reported differences in step length [19] and ground contact time [20][21] compared with uphill and level running, and an interaction between speed and gradient has also been observed [22]. These findings suggest that the technical characteristics of high-speed downhill running may exhibit greater specificity. Consequently, the effects of high-speed, resisted, and downhill conditions on the spatiotemporal characteristics of the push phase warrant investigation, which also represents an important research direction for properly understanding bobsleigh pushing and for preventing athlete injuries.

Spatiotemporal parameters are the most direct indicators for characterising changes in a sport. The spatiotemporal variables of each gait cycle during running collectively regulate and optimise the various sub-phases of the stride [23][24]. Appropriate combinations of these parameters can optimise running kinetics and improve running economy [25], while spatiotemporal measures also serve as useful predictors of injury risk [26][27]. Therefore, examining the spatiotemporal characteristics of the bobsleigh push phase provides an initial observational window to reveal land-ice differences and serves as a logical starting point for further investigation of sport-specific technical features. A systematic comparison of spatiotemporal variables helps to uncover the distinctions between land-based and ice-based bobsleigh pushing.

Methods

Participants

The present study involved 10 active male athletes from the national bobsleigh team. Spatiotemporal parameters were collected during land-based and ice-based pushing across the start, acceleration, and high-velocity phases. All participants were international-level athletes with extensive experience in four-man bobsleigh pushing and competition, and none reported any injury prior to testing. The athletes were assigned to the following positions: pilot ($n = 2$), pusher ($n = 4$), and brakeman ($n = 4$).

Test Equipment and Field Setup

A Fastmove markerless automatic recognition motion capture system (RuiDong Technology, sampling frequency 100 Hz, Dalian, China) was used to collect kinematic data during the start, acceleration, and high-velocity phases of four-man bobsleigh pushing. Due to environmental constraints and safety considerations, cameras were positioned on both sides of the track for land-based testing, whereas for ice-based testing cameras were placed on the left side of the track. A 50-m straight section of a standard athletic track was selected as the land-based push test site. The first 30 m were designated as the push zone, and the remaining 20 m (30–50 m) served as a deceleration buffer safety zone. The camera capture area was established at approximately 20 m from the start line, with the field of view covering at least one complete stride cycle of the push. The start phase was defined within this capture area. The acceleration phase began 5 m from the start point, and the high-velocity phase began 20 m from the start point. Video recordings were obtained separately for each phase (start, acceleration, and high-velocity) of the push technique. The coordinate system was defined with the X-axis aligned with the pushing direction, the Y-axis horizontal to the left of the athlete, and the Z-axis vertical (Fig. 1). For land-based pushing, a simple practice sled used by the national team was employed, with a total load of 100 kg. For ice-based testing, a competition-specification four-man bobsleigh with a mass of 220 kg was used (Fig. 2).

Test Protocol

Prior to formal testing, all participants completed a full warm-up and the necessary preparatory procedures. After each land-based push trial, athletes returned to the designated start position and awaited the next trial. For ice-based testing, athletes changed into sliding suits and spiked

ice shoes before the test commenced. Push times were recorded using the track timing system. Athletes performed maximal-effort pushes from their respective positions and transitioned into the glide phase; video recording continued until the sled had completely left the camera field of view.

Data Processing

For analysis of the start, acceleration, and high-velocity phases, one complete stride cycle was selected from the push start, at 5 m, and at 20 m, respectively. A complete stride cycle consisted of the stance and swing phases of the same leg. Within the swing phase, the period from toe-off to the instant when the knee reached its highest position was defined as the initial swing phase; the period from the highest knee position to foot-strike was defined as the terminal swing phase. Kinematic data of the push technique were processed using Fastmove 3D Motion software (RuiDong Technology, Dalian, China). Video sequences were automatically digitised based on the artificial-intelligence joint-recognition function, followed by manual correction. The data were smoothed with a fourth-order Butterworth low-pass filter (cut-off frequency 10 Hz).

Three-dimensional coordinates were reconstructed using the DLT (direct linear transformation) method, yielding kinematic parameters for the start, acceleration, and high-velocity phases of pushing. Given the limited sample size, Bayesian independent-samples tests were employed to assess between-condition differences. A Bayes factor (BF10) greater than 3 was interpreted as moderate evidence in favour of the alternative hypothesis[28], and a 95% credible interval for the posterior mean difference not containing zero was taken as further support for consistency in the direction of the difference.

Results

Comparison of Spatiotemporal Gait Parameters Between Land-Based and Ice-Based Pushing

Table 1
Gait Cycle Spatiotemporal Parameters: Land vs. Ice Comparison by Position and Phase in Bobsleigh Push ($\bar{X} \pm S$)

			Stride length (m)	Step frequency (Hz)	Stride duration (s)	Double support time (s)	Single support time (s)	Swing time (s)	Flight time (s)
Pilot	Strat	land	1.501 $\pm$ 0.031	1.417 $\pm$ 0.071*	1.413 $\pm$ 0.071*	0.853 $\pm$ 0.062*	0.230 $\pm$ 0.012	0.334 $\pm$ 0.006*	0.092 $\pm$ 0.012
		ice	1.446 $\pm$ 0.183	1.992 $\pm$ 0.035	1.005 $\pm$ 0.018	0.486 $\pm$ 0.074	0.229 $\pm$ 0.035	0.290 $\pm$ 0.021	0.065 $\pm$ 0.021
	Acceleration	land	2.144 $\pm$ 0.185	3.84 $\pm$ 0.083	0.521 $\pm$ 0.011*	---	0.173 $\pm$ 0.014	0.348 $\pm$ 0.027	0.188 $\pm$ 0.029*
		ice	2.048 $\pm$ 0.040	4.035 $\pm$ 0.138	0.496 $\pm$ 0.017	---	0.188 $\pm$ 0.012	0.309 $\pm$ 0.029	0.121 $\pm$ 0.023
	High-velocity	land	2.838 $\pm$ 0.091	3.868 $\pm$ 0.000*	0.517 $\pm$ 0.000*	---	0.14 $\pm$ 0.003*	0.377 $\pm$ 0.003*	0.236 $\pm$ 0.002*
		ice	2.774 $\pm$ 0.023	4.594 $\pm$ 0.097	0.436 $\pm$ 0.009	---	0.125 $\pm$ 0.006	0.311 $\pm$ 0.015	0.190 $\pm$ 0.021
Pusher	Strat	land	1.606 $\pm$ 0.259	1.259 $\pm$ 0.130*	1.603 $\pm$ 0.171*	1.007 $\pm$ 0.190*	0.263 $\pm$ 0.015*	0.332 $\pm$ 0.038	0.051 $\pm$ 0.045
		ice	1.743 $\pm$ 0.081	1.875 $\pm$ 0.108	1.069 $\pm$ 0.059	0.583 $\pm$ 0.052	0.188 $\pm$ 0.026	0.299 $\pm$ 0.012	0.047 $\pm$ 0.015
	Acceleration	land	2.268 $\pm$ 0.090	3.669 $\pm$ 0.092	0.545 $\pm$ 0.013	---	0.210 $\pm$ 0.015	0.337 $\pm$ 0.012	0.144 $\pm$ 0.021
		ice	2.292 $\pm$ 0.173	3.845 $\pm$ 0.518	0.525 $\pm$ 0.071	---	0.206 $\pm$ 0.033	0.317 $\pm$ 0.041	0.136 $\pm$ 0.026
	High-velocity	land	2.852 $\pm$ 0.146	3.978 $\pm$ 0.202	0.504 $\pm$ 0.025	---	0.150 $\pm$ 0.013*	0.355 $\pm$ 0.017	0.213 $\pm$ 0.013
		ice	3.081 $\pm$ 0.171	4.279 $\pm$ 0.349	0.469 $\pm$ 0.038	---	0.117 $\pm$ 0.000	0.352 $\pm$ 0.038	0.240 $\pm$ 0.026
Brakeman	Strat	land	1.619 $\pm$ 0.152	1.297 $\pm$ 0.134*	1.556 $\pm$ 0.167	1.029 $\pm$ 0.165	0.175 $\pm$ 0.034	0.352 $\pm$ 0.024*	0.077 $\pm$ 0.026*
		ice	1.456 $\pm$ 0.129	1.681 $\pm$ 0.369	1.529 $\pm$ 0.121	1.023 $\pm$ 0.140	0.212 $\pm$ 0.030	0.294 $\pm$ 0.017	0.039 $\pm$ 0.004
	Acceleration	land	2.272 $\pm$ 0.045*	3.758 $\pm$ 0.143	0.533 $\pm$ 0.020	---	0.190 $\pm$ 0.014	0.344 $\pm$ 0.015	0.162 $\pm$ 0.016
		ice	2.115 $\pm$ 0.176	3.69 $\pm$ 0.000	0.542 $\pm$ 0.000	---	0.209 $\pm$ 0.018	0.334 $\pm$ 0.018	0.167 $\pm$ 0.029
	High-velocity	land	2.869 $\pm$ 0.111*	3.936 $\pm$ 0.248	0.510 $\pm$ 0.034	---	0.138 $\pm$ 0.012	0.372 $\pm$ 0.024	0.235 $\pm$ 0.019
		ice	3.115 $\pm$ 0.021	4.211 $\pm$ 0.050	0.475 $\pm$ 0.006	---	0.132 $\pm$ 0.015	0.344 $\pm$ 0.008	0.221 $\pm$ 0.018

Note. * indicates BF10 > 3 and the credible interval excludes zero. Same notation is used in subsequent tables.

Spatiotemporal gait parameters showed systematic differences between land-based and ice-based pushing across positions and phases (Table 1). Overall, compared with ice-based pushing, land-based pushing exhibited longer stride duration, longer stance time, longer swing time, and lower step frequency, with these characteristics being more pronounced at the pilot and pusher positions. Statistical results indicated that during the start phase, land-based pushing showed lower step frequency, longer stride duration, and longer swing time than ice-based pushing across all positions. During the high-velocity phase, the brakeman position showed shorter stride length in land-based than in ice-based pushing, while the pilot and pusher positions showed longer stance time and longer swing time in land-based pushing. In the remaining comparisons, although no statistically significant differences were observed, the data still suggested a trend of separation between land-based and ice-based conditions, with land-based pushing generally showing longer durations and lower frequency for most parameters compared with ice-based pushing.

Comparison of Centre of Mass Displacement Parameters Between Land-Based and Ice-Based Pushing

Table 2
Comparison of Vertical and Horizontal COM Displacement Parameters by Position and Phase between Land-Based and Ice-Based Bobsleigh Push ($\bar{X} \pm S$)

			Vertical COM			Horizontal COM			
			Maximum displacement	Mean displacement	Displacement amplitude	Mean velocity (m/s)	Mean acceleration (m/s ²)	Maximum velocity (m/s)	Maximum acceleration (m/s ²)
pilot	start	land	0.405 ± 0.012	0.362 ± 0.010	0.081 ± 0.004	1.243 ± 0.027*	2.043 ± 0.006*	3.050 ± 0.053*	8.882 ± 0.224
		ice	0.395 ± 0.013	0.354 ± 0.001	0.085 ± 0.024	1.820 ± 0.134	3.074 ± 0.239	3.403 ± 0.042	10.441 ± 2.441
	Acceleration	land	0.418 ± 0.012	0.408 ± 0.009	0.022 ± 0.003*	4.486 ± 0.172*	-0.341 ± 0.767*	4.747 ± 0.243*	13.119 ± 4.785
		ice	0.403 ± 0.018	0.387 ± 0.016	0.030 ± 0.003	3.891 ± 0.065	1.419 ± 0.148	4.325 ± 0.177	7.817 ± 0.419
	High-velocity	land	0.442 ± 0.001	0.431 ± 0.000*	0.021 ± 0.002	5.661 ± 0.194*	-2.521 ± 0.169*	6.541 ± 0.437	18.234 ± 4.653
		ice	0.434 ± 0.010	0.423 ± 0.004	0.023 ± 0.01	6.687 ± 0.019	-0.730 ± 1.198	6.810 ± 0.015	13.224 ± 1.46
pusher	start	land	0.414 ± 0.036*	0.343 ± 0.010	0.154 ± 0.051*	1.310 ± 0.263*	1.436 ± 0.302*	2.703 ± 0.141*	7.47 ± 0.712*
		ice	0.373 ± 0.014	0.331 ± 0.016	0.088 ± 0.005	1.734 ± 0.177	3.305 ± 0.220	3.661 ± 0.286	9.944 ± 1.398
	Acceleration	land	0.406 ± 0.005*	0.387 ± 0.007*	0.035 ± 0.011	4.030 ± 0.137*	-0.497 ± 0.889	4.471 ± 0.120*	18.769 ± 7.436
		ice	0.390 ± 0.000	0.368 ± 0.006	0.035 ± 0.009	4.332 ± 0.112	0.889 ± 0.611	4.799 ± 0.139	12.992 ± 8.717
	High-velocity	land	0.446 ± 0.020	0.424 ± 0.005	0.041 ± 0.027	5.483 ± 0.196*	0.315 ± 1.543*	5.872 ± 0.076*	23.993 ± 10.97
		ice	0.432 ± 0.000	0.417 ± 0.003	0.026 ± 0.006	7.353 ± 0.120	-7.955 ± 2.333	7.353 ± 0.120	23.209 ± 15.767
brakeman	start	land	0.400 ± 0.016*	0.356 ± 0.009*	0.108 ± 0.023*	1.044 ± 0.095	1.705 ± 0.166*	2.819 ± 0.101*	9.824 ± 2.485
		ice	0.376 ± 0.009	0.344 ± 0.004	0.070 ± 0.014	1.044 ± 0.096	2.050 ± 0.151	3.294 ± 0.133	13.397 ± 3.709
	Acceleration	land	0.410 ± 0.012	0.397 ± 0.014	0.027 ± 0.005	4.284 ± 0.151	0.127 ± 1.579	5.715 ± 2.348	18.987 ± 2.681*
		ice	0.406 ± 0.011	0.390 ± 0.012	0.033 ± 0.002	4.003 ± 0.371	1.916 ± 1.007	4.756 ± 0.004	12.846 ± 5.156
	High-velocity	land	0.440 ± 0.003*	0.428 ± 0.003*	0.028 ± 0.004*	5.666 ± 0.249*	0.316 ± 2.233*	6.089 ± 0.384*	21.977 ± 16.237
		ice	0.414 ± 0.007	0.394 ± 0.011	0.039 ± 0.011	7.271 ± 0.072	-5.452 ± 2.306	7.270 ± 0.072	29.979 ± 2.3627

Note. COM: centre of mass. Vertical centre of mass displacement data were normalized by stature; normalized value = raw value / stature. Mean velocity and mean acceleration values were calculated over the entire stride cycle for each phase.

Overall, compared with ice-based pushing, land-based pushing exhibited a trend of greater vertical centre of mass (COM) displacement and lower horizontal velocity and acceleration (Table 2). For vertical COM displacement, the pusher and brakeman positions showed greater maximum displacement, mean displacement, and amplitude in land-based pushing during the start and acceleration phases for most comparisons; the pilot position showed greater mean displacement in land-based pushing during the high-velocity phase but smaller amplitude during the acceleration phase. For horizontal COM displacement, land-based pushing showed significantly lower mean and maximum velocities

than ice-based pushing at the pusher position across all phases, at the brakeman position during the start and high-velocity phases, and at the pilot position during the acceleration and high-velocity phases. Land-based mean acceleration was also generally lower across most phases and positions, except that the brakeman position showed greater maximum velocity during the acceleration phase in land-based pushing.

The temporal changes in vertical centre of mass (COM) displacement during land-based and ice-based pushing are shown in Fig. 3 (Fig. 3). Overall, compared with ice-based pushing, land-based pushing showed greater vertical oscillation and higher peaks during the stance phase across all positions in the start and acceleration phases, whereas ice-based pushing exhibited a smoother trajectory. During the high-velocity phase, the vertical COM displacement patterns for the pilot and brakeman positions tended to converge between land-based and ice-based conditions, although the brakeman position showed a relatively large discrepancy in the displacement curve. For the pusher position, land-based pushing showed markedly higher COM displacement during the terminal swing phase compared with the flatter trajectory observed in ice-based pushing. Across the acceleration and high-velocity phases, the overall trend of vertical COM displacement was similar between land-based and ice-based pushing for all positions, but land-based values remained almost consistently higher than those on ice.

Discussion

Comparison of Spatiotemporal Gait Parameters

Start Phase

In the comparison of spatiotemporal gait parameters, the higher step frequency and shorter swing and flight times during the start phase may be related to the harder and more slippery ice surface. This starting pattern may be more beneficial for maintaining stability on ice, thereby allowing athletes to obtain ground reaction forces more effectively during pushing. Research on ice-surface running is limited; among similar sports, only skeleton involves a similar ice-based push start. Although no comparative studies of spatiotemporal parameters between land-based and ice-based skeleton pushing were identified, kinematic research on ice-based skeleton pushing has reported that higher-level athletes adopt a relatively shorter step length and higher step frequency during the early acceleration phase[29].

The differences in spatiotemporal parameters across positions between land-based and ice-based starts indicate that the gait pattern during the ice-based start is more compact, with more active leg swing and earlier ground contact, thereby shortening the entire stride cycle. The shorter double support time also suggests a more active start pattern for the pilot and pusher positions on ice. These changes may be related to adaptation to team coordination during the ice-based start. In land-based pushing, due to equipment limitations, only one athlete can train at a time and the starting rhythm is self-controlled, whereas team pushing on ice requires faster starts and accelerations, forcing athletes to adjust their starting rhythm to the group. The slightly shorter step length and higher step frequency on ice are also advantageous for accelerating the heavy sled, and may be more energy-efficient to some extent. However, the shorter double support time may reduce some starting explosive power and increase the risk of unstable centre-of-mass transfer, yet the shortened double support phase accelerates the turnover rate of the movement cycle, resulting in a higher initial step frequency.

In sprint start research, it has been suggested that high-level athletes lift the swing leg more quickly, shortening flight time, which helps to direct the ground reaction force more horizontally during the first stance and promotes earlier entry into the second propulsive phase[30][31]. Therefore, the shorter flight time during the ice-based start may allow the lower limbs to adopt a more horizontally-oriented push-off pattern more rapidly. For the brakeman position, the longer single-support time on ice than on land suggests that the brakeman contributes propulsive force with one leg for a longer duration during the start. A longer single-support time alone may reduce step frequency, but the subsequent active swing and early ground contact after support termination compensate for this effect.

Acceleration Phase

During the acceleration phase, the push movement pattern begins to enter a regular ground-contact–support–swing cycle. The more apparent differences in spatiotemporal gait parameters were observed in the brakeman's step length, the pilot's stride duration, and the pilot's flight time. However, closer inspection revealed a general trend across all positions in ice-based pushing compared with land-based pushing: smaller step length, higher step frequency, shorter stride duration, longer stance time, and shorter swing and flight times.

During the acceleration phase on ice, the higher hardness of the ice surface generates greater ground reaction forces during the push run. According to Newton's third law, and in the absence of other factors, a harder ice surface would theoretically produce ground reaction forces equivalent to the athlete's push-off effort. However, the poor elastic deformation of ice may lead to excessive loading on the lower limbs from these ground reaction forces, prompting the athlete to automatically adjust lower-limb stiffness to accommodate the forces and provide self-protection[32]. At the same time, the harder ice surface prevents the lower limbs from utilising greater stretch-reflex and tendon elastic

energy during impact absorption, as occurs in land-based pushing; instead, the "hard" and "slippery" surface favours a more concentric-dominant contraction pattern. Furthermore, ice-based push athletes need to actively push downward to engage the spikes with the ice, generating sustained horizontal propulsive forces, which contributes to the increased stance time. Studies on different surfaces have found that contact time is longer on harder surfaces[12], although the body's active adjustments during locomotion on harder surfaces can partially reduce differences in step frequency, stance time, and peak ground reaction forces compared with other surfaces[12].

The lower friction on ice requires athletes to actively "grip" the ice with their spikes. A shorter step length also facilitates spike penetration into the ice without slipping or "scratching" the surface. At the same time, a shorter step length implies a larger ground contact angle, and an appropriate ground contact angle can positively influence step frequency by affecting braking time[33]. Athletes more actively push the swing leg downward to produce an active pawing action. A longer step length, by contrast, reduces the ground contact angle, increases braking forces, and decreases horizontal velocity[34]. Therefore, during the acceleration phase, the relatively shorter step length in ice-based pushing may not only facilitate "gripping" the ice but also help reduce horizontal braking forces on the harder ice surface—a finding also observed in the acceleration phase of skeleton pushing[29]. The shorter swing and flight times reflect the athlete's active downward leg action after the swing in ice-based pushing, while also increasing step frequency to compensate for any potential negative effects of the shorter step length.

High-Velocity Phase

Comparisons of parameters during the high-velocity phase revealed that ice-based pushing generally showed higher step frequency and shorter phase durations across all positions, except for the pusher position, where both step length and flight time increased simultaneously. During the high-velocity phase, apart from surface differences, the most substantial difference between land-based and ice-based pushing is the presence of an approximately 12% downhill gradient on the ice track during this phase[17], whereas land-based pushing remains on a level surface throughout.

A systematic review of studies on graded running analysed spatiotemporal parameters under different speeds and gradients. Based on 15 included studies, the review concluded that significant differences in spatiotemporal parameters were primarily observed in uphill running[35][36][37], whereas changes in spatiotemporal parameters during downhill running showed no consistent pattern[18]. Nevertheless, individual studies have reported that downhill running tends to increase stride length, decrease step frequency, reduce swing time, increase flight time, and increase contact time as gradient decreases[21]. These findings collectively suggest that level and downhill running may differ in spatiotemporal parameters, although the running speeds in these studies were limited[18].

In the present study, the primary gradient change occurs during the high-velocity phase. Unlike previous studies, during bobsleigh pushing the sled accelerates under gravity, forcing athletes to adjust their running pattern to keep up with the sled and provide maximal additional acceleration. This task-environment coupling may be the direct cause of the differences between land-based and ice-based pushing in the high-velocity phase. Therefore, compared with the general trends reported in previous downhill running studies, ice-based pushing in the present study showed an increased step frequency relative to land-based pushing, with the pusher and brakeman positions maintaining increased step length, while stance time decreased across all positions and flight time tended to decrease.

Comparison of Centre of Mass Motion

Start Phase

During the start phase, the vertical and horizontal centre of mass (COM) displacement reflect the athlete's ability to generate forward velocity rapidly. It is generally recognised that in sprint-type movements, the start should aim for greater horizontal COM displacement and as small a vertical COM displacement as possible[38]. Horizontal displacement influences forward acceleration, while vertical displacement is negatively associated with performance [39], and an optimal balance between the two is required for an economical and efficient starting technique[40].

Compared with land-based pushing, the pilot position showed no statistically significant differences in vertical parameters during the start, but the vertical COM displacement during the stance phase on ice was noticeably smaller and smoother. Similarly, for the pusher and brakeman positions, vertical COM displacement was smaller and smoother on ice, and for the brakeman, all indices were lower on ice than on land, with the stance-phase vertical COM displacement being smaller on ice. These findings indicate that during the ice-based start, athletes across all positions reduced vertical motion and directed more effort horizontally, thereby shortening start time and improving overall start efficiency.

Several factors may explain the differences in vertical COM displacement during the start between land-based and ice-based pushing. First, land-based pushing is performed individually: during the start, the pilot and pusher athletes rely more on their body weight to overcome inertia, generating a forward-tilting gravitational moment that converts some vertical gravitational potential energy into a horizontal component. This results in greater vertical COM oscillations during the stance phase, as athletes attempt to use body-weight impact to reduce lower-limb push-off loads. However, this is a relatively inefficient start strategy, leading to insufficient horizontal impulse, increased overall start time, and energy waste. In actual competition, because the sled differs from the training sled, continuing to use a "dive" start would cause the upper body to lean over the handle, increasing the downward force component, shortening the lower-limb moment arm, reducing forward propulsion,

prolonging start time, and attenuating initial acceleration. Second, the handle height of the land-based training sled is higher than that of the competition sled used on ice; therefore, during land training the handle height is greater, and the vertical COM displacement during the start increases accordingly to maintain balance and optimal force-generating posture.

From the horizontal displacement indices during the start, the pilot and pusher positions generally showed greater horizontal COM displacement values on ice than on land for most variables, which is consistent with the view that excessive vertical COM changes on land negatively affect horizontal velocity. For the brakeman, the mean velocity was nearly identical between conditions, but the mean acceleration and maximum velocity on ice were greater than on land, further indicating that smaller and smoother vertical COM displacement on ice still positively contributes to horizontal velocity.

Acceleration Phase

During the acceleration phase, vertical COM displacement across all positions tended to stabilise. The pusher position showed smaller maximum and mean vertical COM displacement on ice than on land, whereas the pilot position showed greater vertical amplitude on ice. Although no statistically significant differences were observed for the remaining indices, overall vertical COM displacement on ice tended to be smaller than on land. As the push enters the acceleration phase, the push pattern gradually becomes periodic and steady on both surfaces, with the upper body posture largely fixed and the lower limbs alternating support and swing phases; thus, large differences in vertical COM displacement between land and ice are not expected.

The greater vertical amplitude at the pilot position on ice during the acceleration phase indicates a gradual elevation of the COM, while land-based pushing remained more stable; the pusher showed similar amplitudes on both surfaces, and the brakeman's larger amplitude on ice also reflected a tendency for COM elevation. The gradual rise in COM during the acceleration phase is a natural consequence of movement, and maintaining a stable vertical COM does not substantially affect horizontal velocity development.

For horizontal COM displacement, the pilot position showed significantly lower mean and maximum velocities on ice than on land, but higher mean acceleration. At the pilot position in land-based pushing, a clear negative acceleration was observed at the beginning of the stance phase, indicating a transient decrease in horizontal COM velocity, most likely due to notable braking forces upon ground contact. Classic sprint studies have reported a mean braking force of -153 ± 67 N during the braking phase, with a $\sim 4.8\% \pm 2.9\%$ decrease in horizontal COM velocity over a duration of only 0.022 ± 0.005 s[41]. In the present study, the decrease in horizontal COM velocity during the acceleration phase for the pilot on land lasted approximately 5% of the stride cycle, about 0.026 s, which closely matches the literature values. Thus, it is plausible that the pilot experienced substantial braking during this phase on land, affecting overall mean acceleration. On ice, no marked negative acceleration was observed during the stance phase; only a slight reduction occurred, indicating a slower increase in horizontal velocity. Therefore, during the ice-based acceleration phase, the pilot's horizontal COM velocity was affected at the start of stance, but to a lesser extent than on land. Combined with the spatiotemporal gait parameters, the shorter step length on ice may be the primary factor reducing horizontal braking forces.

For the pusher and brakeman positions, the land-based mean acceleration may also be influenced by early-stance braking, but the pusher's overall velocity on ice was greater and showed less fluctuation than on land. Although the brakeman and pilot showed stable velocity on ice, both were lower than on land, suggesting that factors beyond braking—possibly other mechanical constraints—influence the acceleration phase on ice, warranting further investigation.

High-Velocity Phase

During the high-velocity phase, vertical COM displacement became more stable across all positions. The pilot showed smaller mean vertical COM displacement on ice than on land; the pusher showed no significant differences; and the brakeman showed smaller maximum and mean displacement but greater amplitude on ice than on land. In this phase, the downhill gradient and the athletes' preparation for jumping onto the sled also influence vertical COM displacement on ice. Studies on downhill running have reported that as gradient increases, runners tend to lean backward[42], and the COM performs mainly negative work during downhill running[43]. Additionally, vertical COM displacement decreases in downhill running, possibly to reduce impact forces and injury risk[44][45]. In the high-velocity phase of ice-based bobsleigh pushing, the pilot, pusher, and brakeman all showed smaller vertical and mean COM displacements than on land, and the presence of the sled in front provides support against downhill inertia, while the higher step frequency in this phase also helps maintain a relatively low COM.

For horizontal COM displacement, mean and maximum velocities on ice were greater than on land across all positions. Mean acceleration was lower on ice than on land for all positions except the pilot, and maximum acceleration was greater on ice only for the brakeman. Overall, velocity was higher on ice, but acceleration decay was greater for the pusher and brakeman during the high-velocity phase; the pilot also showed acceleration decay but to a lesser extent than on land.

The primary cause of reduced mean acceleration appears to be the larger braking forces during the early stance phase on ice. Compared with level and uphill running, downhill running impact forces increase with gradient[46], and peak braking force increases while peak propulsive force decreases[35], which may lead to acceleration reduction during stance. The ice surface itself is harder than land; studies have shown that

reducing surface hardness during downhill running can decrease the anterior-posterior ground reaction force by 56% [47], indirectly supporting the notion that horizontal posterior ground reaction forces are higher during the stance phase on ice at high speed. However, the pilot showed less horizontal acceleration decay at the beginning of stance on ice than on land, suggesting that despite various unfavourable conditions, the pilot adjusted step length, step frequency, and flight time to minimise horizontal braking and vertical impact. Although braking magnitude was reduced, the deceleration duration during stance was proportionally longer on ice (about 10% of the stride cycle) than on land (about 5%), which also hindered velocity improvement.

For the pusher and brakeman, the lower mean acceleration was mainly due to a pronounced decrease in acceleration during the swing phase. Overall acceleration profiles during the high-velocity phase showed that the pusher and brakeman could maintain velocity only during the stance and early initial swing phases, after which acceleration began to decline continuously. Given the practical context of ice-based pushing at high speed, this acceleration decay suggests a possible velocity mismatch between the athletes and the sled. Considering that the pilot and pusher may prepare to jump onto the sled, it cannot be ruled out that unintentional backward pulling of the sled occurs, which would cause acceleration to drop. However, this hypothesis requires more detailed measurements of forces and velocity changes of both the sled and the athletes to confirm.

Previous research has suggested that the velocity during the bobsleigh push phase accumulates gradually, with acceleration generated entirely by the athletes on the level section, and that the athletes' contribution to velocity decreases rapidly once the downhill section begins[48]. Therefore, if one team member experiences a speed mismatch, the overall push velocity of the team is affected. From the mean acceleration data and practical observations, the pilot is already preparing to jump onto the sled during the high-velocity phase and may complete the jump within the next stride cycle; this may lead to unintentional sled-pulling earlier in the high-velocity phase, contributing to the deceleration observed in the pusher and brakeman. Alternatively, it is also possible that the pusher and brakeman begin to decelerate on their own during this phase. Some evidence suggests that the brakeman may be the strongest pusher in the team[49], making it less likely that the brakeman would fail to keep up with the sled immediately after the pilot mounts. However, because the present study did not measure sled velocity or acceleration, and the complex cooperative effects in four-man pushing cannot be fully captured with a limited number of trials and simplified models, the possibility that the brakeman exerts a backward pulling force on the sled during the high-velocity phase cannot be excluded.

Conclusions

Overall, ice-based pushing exhibited a spatiotemporal pattern characterised by higher step frequency, a more compact stride cycle, and more stable centre-of-mass (COM) displacement. During the start and acceleration phases, the shorter step length and higher step frequency represent a functional adaptation to the low-friction, high-hardness ice surface, facilitating stable ground reaction force application and rapid sled acceleration on the slippery surface; team coordination also contributed to the observed differences. The shorter swing and flight times reflected more active leg swing and downward pawing, which likely increased shoe-ice friction. The relatively longer stance time may be an adaptive response to the greater ice hardness; the combined effect of longer stance time and shorter step length may support sustained horizontal propulsive force production. During the high-velocity phase, the concurrent increases in step length and step frequency, together with reductions in stance, swing, and flight times, arose from the combined demands of maintaining sled propulsion and accommodating the downhill gradient; high neuromuscular control and coordination ensured stability during high-speed downhill pushing.

Land-based training for the start and acceleration phases may carry a risk of negative transfer to ice-based pushing. In the start phase, land-based pushing showed greater vertical COM displacement and lower horizontal velocity, suggesting lower starting efficiency, possibly related to differences in push-bar height between the training sled and the competition sled. In the acceleration phase, the pilot showed lower horizontal acceleration in land-based pushing, most likely associated with higher braking forces at ground contact, whereas the shorter step length on ice may have reduced braking. High-velocity phase training on land may fail to provide the sport-specific stimulus required for ice-based pushing; the combination of downhill gradient and harder ice surface increases braking forces during stance, which appears to be an important factor limiting horizontal COM velocity, and indirectly suggests that athletes may face difficulty in continuously matching sled velocity during the high-speed downhill section.

Training Recommendations

During land-based push training, the start habits of the pilot and pusher positions—characterised by excessive vertical COM oscillation—should be modified. Training should emphasise a horizontally-oriented push-off pattern to improve start efficiency, and the land-based start rhythm should be accelerated to better match the ice-based start. Moderate increases in push load during the start and acceleration phases of land-based training are recommended to enhance step frequency and propulsive force. Incorporation of overspeed running drills may reduce acceleration decay and improve neuromuscular control at high velocities. Creating downhill conditions for land-based push training could help establish training consistency between land and ice during the high-velocity phase. Additional lower-limb eccentric and plyometric training should be implemented to prepare athletes for the high impact forces encountered during ice-based pushing, together with enhanced monitoring and recovery strategies during ice-based training periods.

Limitations and Future Directions

The study was limited to male national-team bobsleigh athletes, and the relatively small sample size warrants caution in generalising the findings. Sled horizontal velocity was not measured or analysed, and lower-limb kinetic data were not collected during ice-based pushing due to safety concerns; consequently, some observations could only be interpreted speculatively. The complex interplay between environmental and task constraints during the high-velocity phase on ice further complicated the analysis, and the effects of surface and gradient on gait were not quantitatively examined.

Future studies should recruit a larger number of eligible participants to verify the generalisability of the findings. Whenever technically feasible and safe, lower-limb kinetic measurements during ice-based pushing should be incorporated, and additional testing modalities for the high-velocity phase should be developed to enable deeper biomechanical characterisation of ice-based bobsleigh pushing.

Abbreviations

- BF10
- Bayes factor
- COM
- Centre of mass
- DLT
- Direct linear transformation

Declarations

Ethics approval and consent to participate

The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Research Ethics Committee of Shanghai University of Sport (approval number: 102772024RT100, date: 9 October 2024). All participants provided written informed consent prior to participation.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Funding

The authors received no specific funding for this work.

Author Contribution

Y.L, B.G, and L.M contributed to the study conception and design. B.G provided the experimental feasibility and resource provision. Y.L, X.D, and B.G performed the data collection. Y.L and M.G performed the formal analysis and data interpretation. Y.L drafted the original manuscript. L.M critically revised the manuscript for important intellectual content and supervised the study. All authors read and approved the final manuscript.

Acknowledgements

Not applicable.

Data Availability

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

References

1. Dabnichki P, Avital E. Influence of the position of crew members on aerodynamics performance of two-man bobsleigh. *J Biomech.* 2006;39(15):2733–42. <https://doi.org/10.1016/j.jbiomech.2005.10.021>.
2. Morlock M, Zatsiorsky V. Factors influencing performance in bobsledding: I: influences of the bobsled crew and the environment. *Int J Sport Biomech.* 1989;5(2):208–21. [No DOI].
3. Brüggemann GP, Morlock M, Zatsiorsky VM. Analysis of the bobsled and men's luge events at the XVII Olympic Winter Games in Lillehammer. *J Appl Biomech.* 1997;13:98–108. <https://doi.org/10.1123/jab.13.1.98>.
4. Wang ZT, Wang XQ, Wu Y. Research on sliding tracks classification based on bobsleigh push-start ability. *Bull Sport Sci Technol.* 2022;30(5):1–5. <https://doi.org/10.19379/j.cnki.issn.1005-0256.2022.05.001>.
5. Tian G, Zhu H, Gong M, Wang D, Gao BH. Effect of post-activation potentiation on sprint ability of national skeleton athletes. *China Sport Sci Technol.* 2022;58(11):38–42. <https://doi.org/10.16470/j.csst.2022043>.
6. Liu Y, Gao BH, Mao LJ. Effect of the bobsleigh push time on race outcomes and the enlightenments for training. *China Sport Sci Technol.* 2024;60(12):3–9. <https://doi.org/10.16470/j.csst.2024093>.
7. Wang GZ, Wang WL, Gao X, Liu Y, Zhang W. Reasons for the low frictional coefficient of ice surface: progress and model analysis. *Univ Chem.* 2019;34(1):33–8. [No DOI].
8. Atila A, Sukhomlinov SV, Müser MH. Cold self-lubrication of sliding ice. *Phys Rev Lett.* 2025;135(6):066204. <https://doi.org/10.1103/PhysRevLett.135.066204>.
9. Bonn D, et al. Friction on ice: how temperature, pressure, and speed control the slipperiness of ice. *Phys Rev X.* 2021;11(1):011044. <https://doi.org/10.1103/PhysRevX.11.011044>.
10. Kong X, Wang D, Zhou X, et al. Runner-ice friction models for winter olympic bobsleigh. *Tribol Int.* 2025;208:110650. <https://doi.org/10.1016/j.triboint.2025.110650>.
11. Park JJ, Kim KH, Park SB. The analysis of foot pressure and lap time for the development of Korean bobsleigh shoes. *Korean J Sport Biomech.* 2015;25(4):465–74. <https://doi.org/10.5103/KJSB.2015.25.4.465>.
12. Fu W, Fang Y, Liu SMD, et al. Surface effects on in-shoe plantar pressure and tibial impact during running. *J Sport Health Sci.* 2015;4(4):384–90. <https://doi.org/10.1016/j.jshs.2015.01.003>.
13. Ferris DP, Louie M, Farley CT. Running in the real world: adjusting leg stiffness for different surfaces. *Proc R Soc Lond B Biol Sci.* 1998;265(1400):989–94. <https://doi.org/10.1098/rspb.1998.0388>.
14. Kerdok AE, Biewener AA, McMahon TA, et al. Energetics and mechanics of human running on surfaces of different stiffnesses. *J Appl Physiol.* 2002;92(2):469–78. <https://doi.org/10.1152/japplphysiol.00305.2001>.
15. Hardin EC, Van Den Bogert AJ, Hamill J. Kinematic adaptations during running: effects of footwear, surface, and duration. *Med Sci Sports Exerc.* 2004;36(5):838–44. <https://doi.org/10.1249/01.MSS.0000126605.65966.40>.
16. Dixon SJ, Collop AC, Batt ME. Surface effects on ground reaction forces and lower extremity kinematics in running. *Med Sci Sports Exerc.* 2000;32(11):1919–26. <https://doi.org/10.1097/00005768-200011000-00014>.
17. International Bobsleigh and Skeleton Federation. IBSF Track Rules [Internet]. 2019 [cited 2025 Apr 19]. Available from: https://www.ibsf.org/images/documents/downloads/Rules/2019_2020/IBSF_Track_Rules_am2019.pdf. [No DOI].
18. Marszałek P, Przednowek K, França C, et al. Change in spatiotemporal parameters during running at different degrees of inclination: systematic review. *Appl Sci.* 2024;14(23):11301. <https://doi.org/10.3390/app142311301>.
19. DeVita P, Janshen L, Rider P, et al. Muscle work is biased toward energy generation over dissipation in non-level running. *J Biomech.* 2008;41(16):3354–9. <https://doi.org/10.1016/j.jbiomech.2008.09.027>.
20. Thomson A, Whiteley R, Hansen C, et al. Effect of speed and gradient on plantar force when running on an AlterG® treadmill. *BMC Sports Sci Med Rehabil.* 2021;13:34. <https://doi.org/10.1186/s13102-021-00260-4>.
21. Park SK, Jeon HM, Lam WK, et al. The effects of downhill slope on kinematics and kinetics of the lower extremity joints during running. *Gait Posture.* 2019;68:181–6. <https://doi.org/10.1016/j.gaitpost.2018.11.022>.
22. Zignoli A, Godin A, Mourot L. Indoor running temporal variability for different running speeds, treadmill inclinations, and three different estimation strategies. *PLoS ONE.* 2023;18:e0287976. <https://doi.org/10.1371/journal.pone.0287976>.
23. Padulo J, Annino G, Smith L, et al. Uphill running at iso-efficiency speed. *Int J Sports Med.* 2012;33:819–23. <https://doi.org/10.1055/s-0032-1311592>.
24. Seidl T, Linke D, Lames M. Estimation and validation of spatio-temporal parameters for sprint running using a radio-based tracking system. *J Biomech.* 2017;65:89–95. <https://doi.org/10.1016/j.jbiomech.2017.10.005>.
25. Lohman III EB, Sackiriyas KSB, Swen RW. A comparison of the spatiotemporal parameters, kinematics, and biomechanics between shod, unshod, and minimally supported running as compared to walking. *Phys Ther Sport.* 2011;12(4):151–63. <https://doi.org/10.1016/j.ptsp.2011.03.001>.

26. Brindle RA, Taylor JB, Rajek C, et al. Association between temporal spatial parameters and overuse injury history in runners: a systematic review and meta-analysis. *Sports Med.* 2020;50(2):331–42. <https://doi.org/10.1007/s40279-019-01207-5>.
27. Heiderscheit BC, Chumanov ES, Michalski MP, et al. Effects of step rate manipulation on joint mechanics during running. *Med Sci Sports Exerc.* 2011;43(2):296–302. <https://doi.org/10.1249/MSS.0b013e3181ebdf4>.
28. Wuttiputhanun T, Udomkarnjananun S, Hanprathet N, et al. Metabolic effects of kidney donation: a Bayesian analysis of matched cohorts. *Nephrol (Carlton).* 2023;28(2):148–53. <https://doi.org/10.1111/nep.14136>.
29. Gong M. Biomechanical characteristics of lower limbs in the push-off phase of elite Chinese skeleton athletes [doctoral dissertation]. Shanghai: Shanghai University of Sport; 2022. <https://doi.org/10.27315/d.cnki.gstyx.2022.000121>
30. Valamatos MJ, Abrantes JM, Carnide F. Biomechanical performance factors in the track and field sprint start: a systematic review. *Int J Environ Res Public Health.* 2022;19(7):4074. <https://doi.org/10.3390/ijerph19074074>.
31. Sandamas PN. Athletic sprint start biomechanics: investigations into the relationships between three dimensional starting technique, first step width and performance [master's thesis]. Stockholm: Gymnastik- och idrottshögskolan; 2021. [No DOI].
32. Zhang Y, Wang L. Influences on sports biomechanics of lower extremities during running on different surfaces. *J Med Biomech.* 2018;33(6):577–. <https://doi.org/10.16156/j.1004-7220.2018.06.016>. 82.
33. Jiang ZL, Li Q, Deng H. Evaluation criteria and regular developing patterns of elite male sprinters' stride length and stride frequency. *J Hebei Sport Univ.* 2016;30(3):64–71. [No DOI].
34. Weyand PG, Sternlight DB, Bellizzi MJ, et al. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol.* 2000;89(5):1991–9. <https://doi.org/10.1152/jappl.2000.89.5.1991>.
35. Gottschall JS, Kram R. Ground reaction forces during downhill and uphill running. *J Biomech.* 2005;38(3):445–. <https://doi.org/10.1016/j.jbiomech.2004.04.023>. 52.
36. Lemire M, Faricier R, Dieterlen A, et al. Relationship between biomechanics and energy cost in graded treadmill running. *Sci Rep.* 2023;13(1):12244. <https://doi.org/10.1038/s41598-023-39123-0>.
37. Telhan G, Franz JR, Dicharry J, et al. Lower limb joint kinetics during moderately sloped running. *J Athl Train.* 2010;45(1):16–21. <https://doi.org/10.4085/1062-6050-45.1.16>.
38. Walker J, Bissas A, Paradisis GP, et al. Kinematic factors associated with start performance in world-class male sprinters. *J Biomech.* 2021;124:110554. <https://doi.org/10.1016/j.jbiomech.2021.110554>.
39. Colyer SL, Graham-Smith P, Salo AIT. Analysis of sprint start transition phases and their associations with performance. In: ISBS-Conference Proceedings Archive. Oxford, UK; 2019:122. [No DOI].
40. Debaere S, Jonkers I, Aerenhouts D et al. Performance determining factors in elite sprinters during sprint start and two following successive supports. In: ISBS-Conference Proceedings Archive. 2010. [No DOI].
41. Mero A. Force-time characteristics and running velocity of male sprinters during the acceleration phase of sprinting. *Res Q Exerc Sport.* 1988;59(2):94–8. <https://doi.org/10.1080/02701367.1988.10605484>.
42. Engeler N, Lichtenstein E, Faude O, et al. How downhill and uphill running interfere posture and muscle activity: a descriptive laboratory study. *Int J Sports Phys Ther.* 2025;20(8):1186–97. <https://doi.org/10.26603/001c.142485>.
43. Luo J. A dynamics research about slope overspeed running training. *J Tianjin Univ Sport.* 2012;27(1):46 – 8, 63. <https://doi.org/10.13297/j.cnki.issn1005-0000.2012.01.017>
44. Lu Z, Suo B, Deng L, et al. A review of uphill and downhill running: biomechanics, physiology and modulating factors. *Front Bioeng Biotechnol.* 2025;13:e1690023. <https://doi.org/10.3389/fbioe.2025.1690023>.
45. Vernillo G, Giandolini M, Edwards WB, et al. Biomechanics and physiology of uphill and downhill running. *Sports Med.* 2017;47(4):615–29. <https://doi.org/10.1007/s40279-016-0605-y>.
46. Wells MD, Dickin DC, Popp J, et al. Effect of downhill running grade on lower extremity loading in female distance runners. *Sports Biomech.* 2020;19(3):333–41. <https://doi.org/10.1080/14763141.2018.1488162>.
47. Casadonte J. The effects of surface compliance on knee joint loads during level and downhill running [doctoral dissertation]. Greenville: East Carolina University; 2020. [No DOI].
48. Dabnichki P et al. Computer analysis of bobsleigh team push. In: Chung P, Soltoggio A, Dawson C, editors. Proceedings of the 10th International Symposium on Computer Science in Sports (ISCSS). Cham: Springer; 2016. pp. 189 – 96. https://doi.org/10.1007/978-3-319-24560-7_25
49. Lee S, Kim T, Lee S, et al. Development of force measurement system of bobsled for practice of push-off phase. *Proc Inst Mech Eng P J Sports Eng Technol.* 2015;229(3):192–8. <https://doi.org/10.1177/1754337115577578>.

Figures

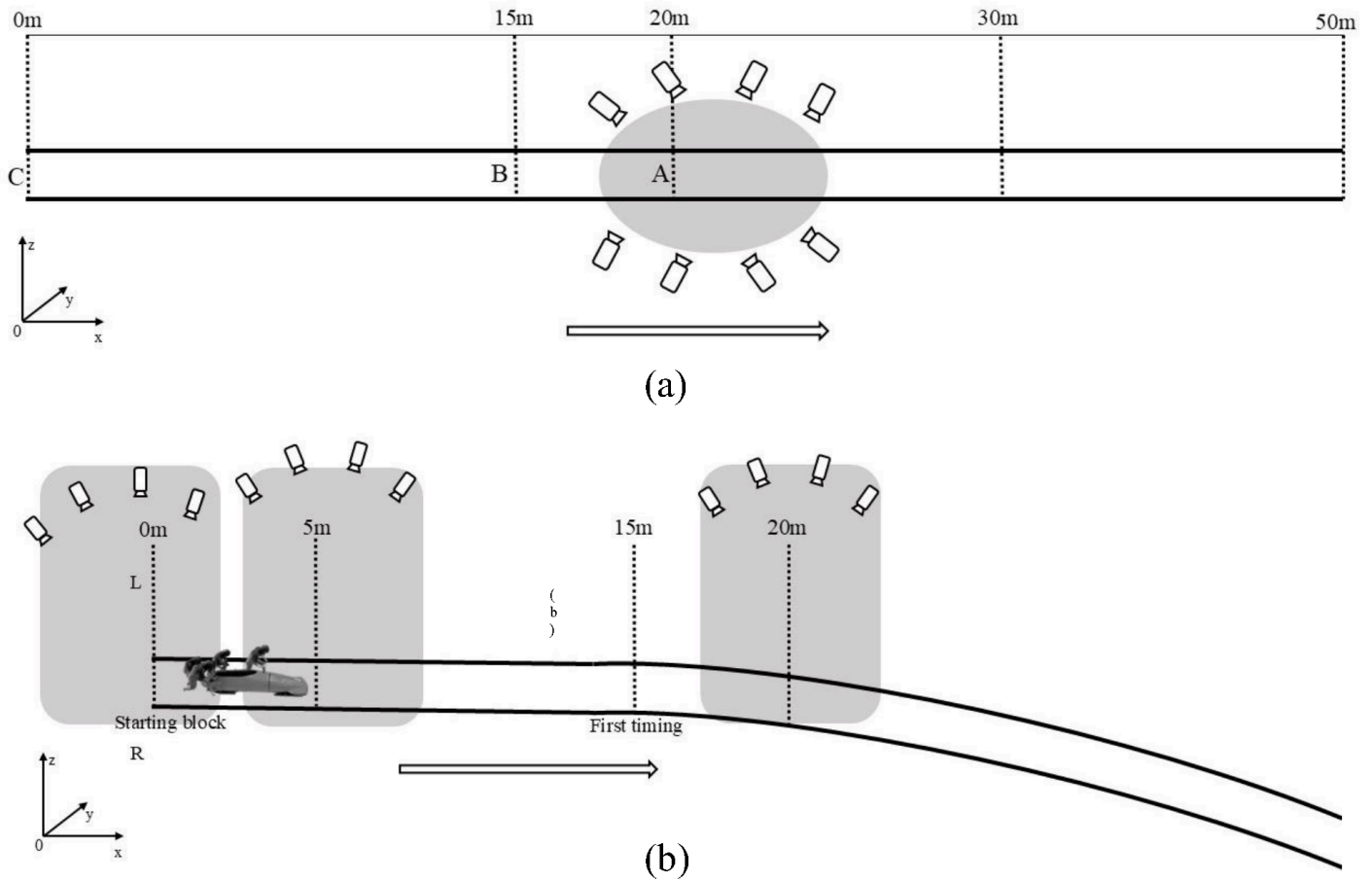


Figure 1

Schematic diagram of the test setup on land and ice track.

(a): Land push. The grey area indicates the capture zone. The arrow indicates the direction of pushing. The solid line represents the push track. Line A marks the start position for the start phase; Line B marks the start position for the acceleration phase; Line C marks the start position for the high-velocity phase. (b): Ice push. The 0 m line marks the start point for the ice-based push.

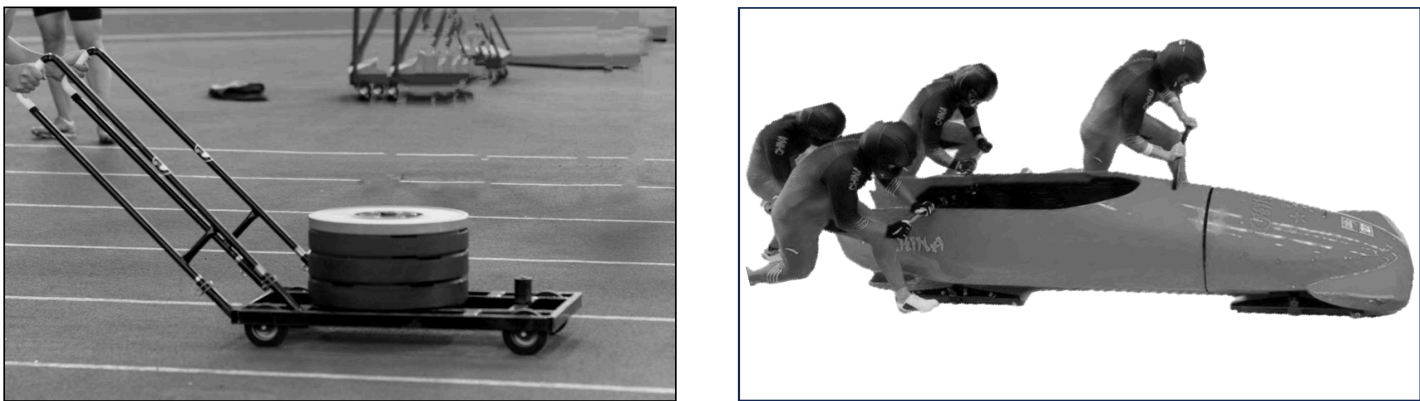


Figure 2

Schematic of the land and ice bobsleigh push setups

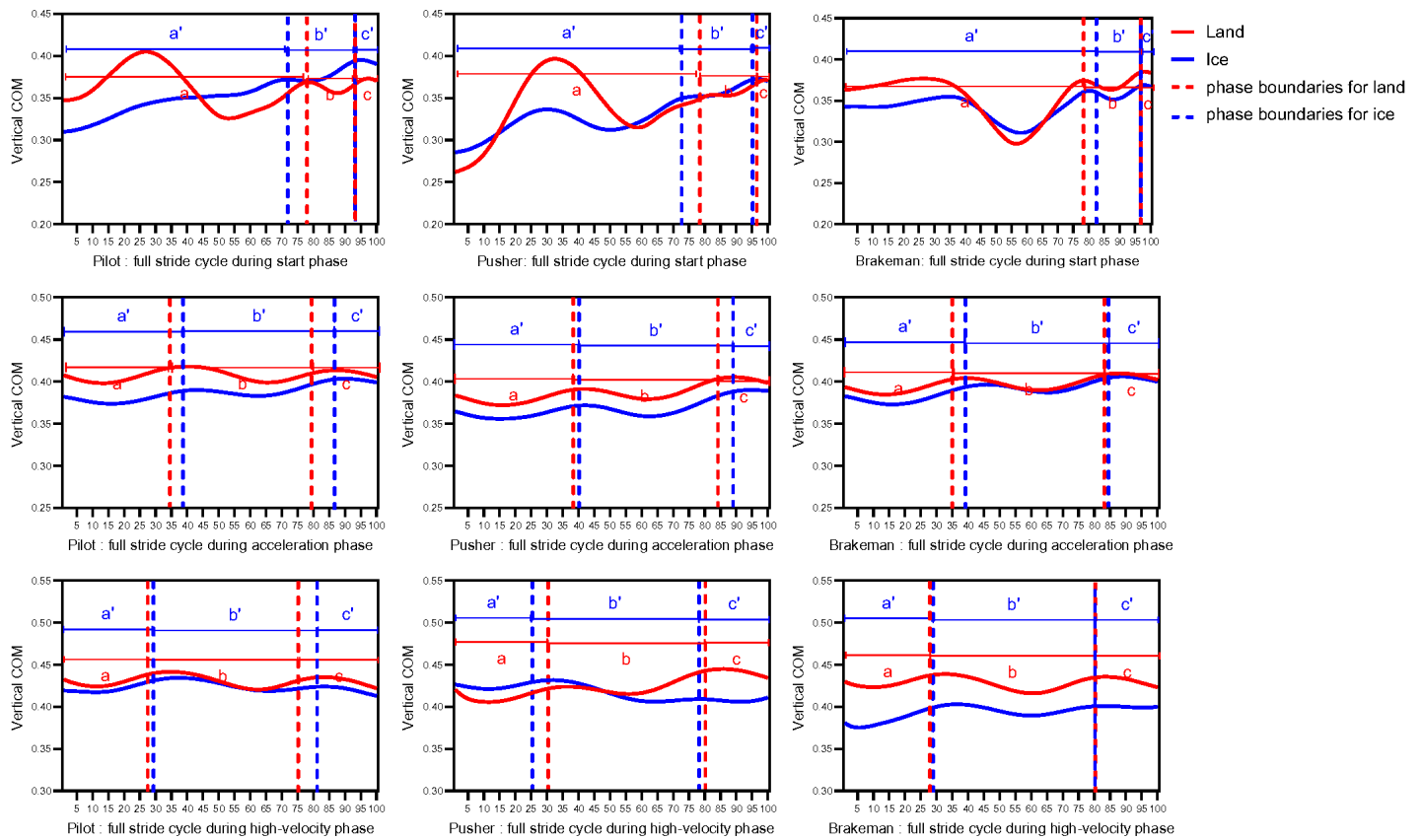


Figure 3

Vertical COM displacement: land vs. ice across phases and positions.

a-c = stance, initial swing, and terminal swing phases of the stride cycle (land); a'-c' = same phases (ice).