



Observation and technical analysis of curve performance in inline speed skating: a systematic review

Observación y análisis técnico del rendimiento en curvas en patinaje de velocidad en línea: una revisión sistemática

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Abstract

Introduction: Inline speed skating remains underexplored in scientific literature, especially on curved sections of the track.

Objective: this systematic review aims to synthesize current research on biomechanical variables, motor patterns, and observational methodologies.

Methodology: following PRISMA guidelines, a systematic search was conducted in Web of Science and PubMed using comprehensive Boolean expressions targeting skating performance and biomechanics.

Results: a total of 5825 articles were initially identified, with 4581 unique records screened. Nine studies met the inclusion criteria, focusing on inline or ice speed skating technique during curves. The studies analysed push-off mechanics, leg asymmetry, body tilt, stroke frequency, and trajectory. Video capture methodologies were consistently employed, often synchronised with electromyographic and force measurement tools.

Discussion: asymmetric push-off behaviour, particularly greater contribution from the left leg during the curve, was a key finding. Trajectory optimization and inward tilt were also correlated with enhanced performance.

Conclusions: the review highlights that biomechanical asymmetries, especially during crossover techniques, play a critical role in speed maintenance through curves. Consistent trunk-pelvis alignment and skating close to the inner curve line were associated with better outcomes.

Keywords

Curve; ice speed skating; inline speed skating; systematic review.

Resumen

Introducción: el patinaje de velocidad en línea sigue siendo un tema poco explorado en la literatura científica, especialmente en lo referente a los tramos curvos de la pista.

Objetivo: esta revisión sistemática tiene como propósito sintetizar la investigación actual sobre variables biomecánicas, patrones motores y metodologías de observación.

Metodología: siguiendo las directrices PRISMA, se realizó una búsqueda sistemática en Web of Science y PubMed utilizando expresiones booleanas amplias dirigidas al rendimiento y la biomecánica del patinaje.

Resultados: se identificaron inicialmente 5825 artículos, de los cuales 4581 registros únicos fueron examinados. Nueve estudios cumplieron los criterios de inclusión, centrados en la técnica del patinaje de velocidad en línea o sobre hielo durante curvas. Los estudios analizaron la mecánica del impulso, la asimetría entre las piernas, la inclinación corporal, la frecuencia de zancada y la trayectoria. Las metodologías de captura de vídeo se emplearon de manera consistente, a menudo sincronizadas con herramientas de electromiografía y medición de fuerzas.

Discusión: uno de los hallazgos clave fue el comportamiento asimétrico del impulso, destacándose una mayor contribución de la pierna izquierda durante la curva. La optimización de la trayectoria y la inclinación hacia el interior también se correlacionaron con un mejor rendimiento.

Conclusiones: la revisión destaca que las asimetrías biomecánicas, especialmente durante las técnicas de cruce, desempeñan un papel fundamental en el mantenimiento de la velocidad en curvas. Una alineación constante entre el tronco y la pelvis, así como el desplazamiento cercano a la línea interna de la curva, se asociaron con mejores resultados.

Palabras clave

Curva; patinaje de velocidad en línea; patinaje de velocidad sobre hielo; revisión sistemática.

Introduction

Inline speed skating (ISS) is characterised as a sport of cyclical techniques and repetitive movements (Bongiorno et al., 2022; Bongiorno, G. & Miceli, L., 2023). Being a discipline with scarce literature and given its similarities to ice speed skating, studies focusing on the biomechanics of ice speed skating serve as valuable references for understanding and transferring to ISS techniques (Boer, 1987b), which combines biomechanics, technique, aerodynamics and physiology to increase speed and efficiency (Boer et al., 1986; Boer, 1987a; Noordhof et al., 2013; Stoter et al., 2020; Krumm et al., 2021; Liu et al., 2024). Even though ISS can be performed indoors, tracks and on roads circuits, these different venues alter the characteristics of the curve section due to variation of inclinations.

In ice speed skating, the position and angles of the legs are very important to the technique and velocity concerning the skater's performance (Noordhof et al., 2013; Noordhof et al., 2014). There are asymmetries between the two legs (Liu et al., 2024), especially with the crossover technique (Boer, 1987a; Boer, 1987b; Boer, 1988; Koning et al., 1991; Kruk et al., 2018a). The push-off mechanics in speed skating is a sideward push that allows the skater to move forward (Soter et al., 2020), and can be studied through push-off angle, knee extension, trunk position or angle, stroke frequency, work per stroke, also body and shank tilts and analysis of the leg muscles through electromyographic analysis (Boer, 1987a; Boer & Nilsen, 1989; Koning et al., 1991; Kruk et al., 2018b).

Video images used as a studying methodology can be helpful to understand with precision the technical and biomechanical aspects when skating (Zhu et al., 2023). The relation of the technique effectiveness and velocity together with the power output is determinant for the skater to overcome frictional forces (Noordhof et al., 2013). As noted on Noordhof et al. (2013) differences of the power output are related to differences of the push-off frequency. Different muscles are used according to the cycle phase, propulsion or recovery (Bongiorno et al., 2024).

Concerning the roller skating disciplines, studies done so far are mainly about physiological analysis and traumatic injuries and, on ISS, Bongiorno et al. (2022, 2023, 2024a) studied electromyographic analysis of the straight technique. Nevertheless, considering the evolution of the ISS and its complex techniques there is a gap in literature regarding the analysis of the curve. Those studies are of paramount importance being a crucial part of the skater's performance on track that require specific adaptations in technique, force distribution, and balance, makes this part of the track as a significant subject to study. Therefore, this systematic review aims to synthesize research on technical analysis, methodologies, and motor patterns evaluated in ISS, providing insights into the essential parameters influencing performance in curved sections of the track. This review raises the essential question of what insights we can gain to organize in a precise way, a set of information that allows us to analyse the athlete's performance. It is expected that the content obtained from this review will come from aspects such as the use of video images in the biomechanical study of athlete performance.

Method

This review followed PRISMA guidelines, which stands for Preferred Reporting Items for Systematic Reviews and Meta-analyses (Page et al., 2021), and the protocol was prospectively registered in PROSPERO (CRD420251004341).

Research Strategy

For this review, the databases Web of Science (WOS) and PubMed, are recognised databases for scientific studies, indexing journals with relevant impact factors, and were used on a search that ended on January 25th, 2025, with no update done after. There were two oldest studies included in this review, both from 1987 and both of the same author, Boer et al., and the most recent was from 2024, Kimura, Y. and Yokozawa, T. The search terms were based on prior reading of several articles, keywords, and specialised knowledge of the sport, and were previously tested for initial verification of results. For search terms were included the Booleans operators ("AND" and "OR") to increase the sensitivity of the search. The following expressions was used: (("inline speed skating" or "roller speed skating" or "speed skating" OR "inline skating" OR skating* OR skater* OR skate* [All fields]) AND (coach* OR sport* OR "high sports



performance” OR theme OR competition* OR curve OR straight OR track OR short track OR road OR “motor pattern*” OR “observational methodology” OR observation OR “observation system” OR technique* OR biomechanics* [All fields])). There was no filter applied to avoid missing potentially relevant studies, which returned 5825 results. Filtering was done later using inclusion/exclusion criteria.

Inclusion/Exclusion Criteria

All records retrieved from PubMed and Web of Science were imported into the Rayyan platform by the first author (LM), where the duplicate entries were removed. Two authors (LM and HL), independently, screened the study titles and abstracts before retrieving and assessing the full texts for eligibility. Any disagreements regarding eligibility were resolved through consultation with the third author (AC). Data extraction was carried out by the first author (LM) using a structured Excel spreadsheet and subsequently verified by the second author (HL). Any inconsistencies were discussed between the two reviewers, and when consensus could not be reached, the third author (AC) was consulted. The extracted information included publication details (author and year), participant characteristics (sample size, gender, height and weight), methodological aspects related to observational methodologies, and biomechanical variables especially on curve analyses regarding crossover and glide techniques, such as body tilt, lower limbs strokes / push-off's, upper limbs positions, trunk position.

Data Extraction

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Quality Assessment and Risk of Bias

A quality assessment of the included studies was conducted using the Critical Appraisal tools for JBI Systematic Reviews, Checklist for Cohort Studies (Tufanaru et al., 2020). The quality assessment for this study used the checklist adapted for cohort studies.

Results

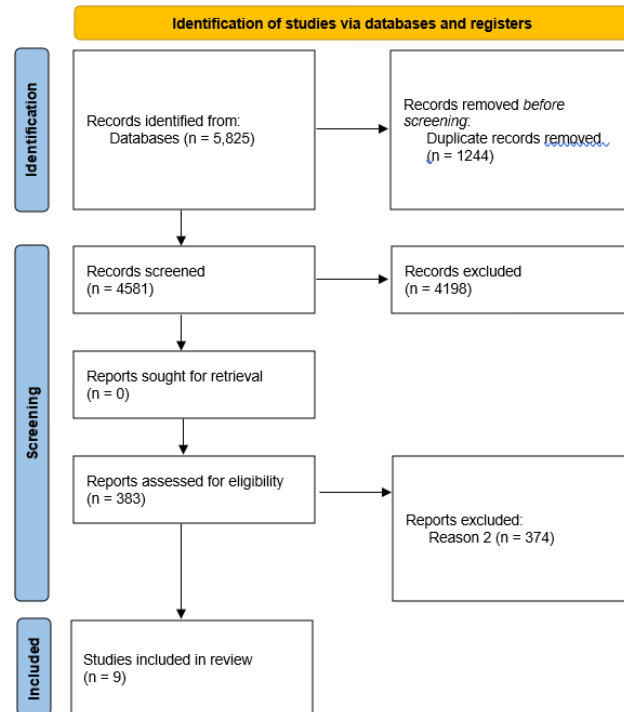
Study Selection

A total of 5825 studies were identified through the database search (Web of Science, n = 2866; PubMed, n = 2959). After remove duplicates, 4581 unique records remained. Based on title and abstract screening, 4198 studies were excluded according the following reasons: i) Studies that don't have inline skating, roller skating or speed skating as a subject (n = 3159); ii) Studies that are not about technique or biomechanics or observation methodology or observation system or observation (n = 1039). To support clarity in the interpretation of the screening process, several technical terms used in this review are briefly defined. “Inline speed skating” and “roller speed skating” refer to speed skating performed on inline wheels, whereas “speed skating” typically denotes being on ice. “Observation methodology” and “observation system” describe structured approaches to analyse technical or behavioural performance. “Biomechanical variables” include kinematic and kinetic measures such as joint angles, velocities, and forces. The term “curve” refers to the curved section of the skating track, where specific technical and mechanical adjustments occur. The term “speed skating” was used on several articles on ice speed skating studies such as Noordhof et al. (2013) or Song et al. (2017), among others. On the other hand, “Inline / Roller Speed Skating”, were used on studies of Bongiorno et al. (2022) or Bongiorno & Micelli, (2023). Terms like “observation methodology” and “observation system” were used on articles such as Sousa et



al. (2023), in this case, related to observation in another sport. The records assessed for eligibility were 383 where 374 were excluded after discussion of the two collaborators and expert using the following criteria: iii) Studies that do not mention curve. Ultimately, 9 studies in this review (figure 1).

Figure 1. Flow chart



Study Summaries

The researched articles studied biomechanical variables such as knee angle, trunk position, push-off angle, skating velocity, segments and articulation or muscles points.

In the searched articles, 4 of them had just male skaters and four just female skaters; 3 articles studied both male and female skaters. Boer, R. W. (1987a), studied 2 male groups and compare them both: i) Elite group; ii) Trained group. Boer & Nilsen (1989), Song (2018) and Kruk et al. (2018a) studied and compared male and female skaters. Boer (1988) and Kimura & Yokozawa et al. (2024) analysed just female skaters.

On all articles video-based image capture. Regarding the outcome measures, biomechanical parameters were mainly used. Koning et al. (1991) also studied muscle activity. One of the articles studied the centre of pressure made on the blade (Kurk et al., 2018).

All articles researched studied skaters' performance when skating the curve (Table 1). Of those, 7 articles included biomechanical variables (Boer, 1987a; Boer, 1987b; Boer, 1988; Boer & Nilsen, 1989; Koning et al., 1991; Song et al., 2019; Kimura & Yokozawa et al., 2024). Of the remaining articles, Hext et al. (2017) studied skaters performance related to the relay race and Kruk et al. (2018a), studied the curve trajectory and also the pressure made on the blade. 6 of the articles investigated official races and 3 were performed with a designed protocol.

Table 1. Summary of the studies included in revision.

Author	N	Gender	Ice/Inline	Methodology	Outcome Measures	Results
Boer et al. (1987a)	G1: 14 G2: 10	M	Ice	Video Images, curve 5000m race	Push-off angle, knee angle, trunk position. Speed, stroke frequency,	Speed, lap and curve, was higher for elite group, Speed and power between groups are different in work per stroke. Greater push-off angle for the elite group.



				NAC motion analyser	speed lap and curve, power stroke.	Left stroke with more powerful push-off in the curve.
Boer et al. (1987b)	8	M	Ice And Inline	4 tests: 2 Ice; 2 Inline Video Images, curve Dynamic Frame motion analyser	Heart rate, aerobic power. knee angle, hip angle, push-off angle. External power	No difference of VO ₂ , ventilation and heart rate. Respiratory exchange ratio ws higher in inline. Similarity of the technique in the two forms of skating, except for the knee angle being smaller on ice. Power stroke is equal.
Boer et al. (1988)	16	F	Ice	Video Images, curve 5000m race NAC motion analyser Curve and	Push-off angles, speed and stroke frequency, external power	Difference between power delivered and power due to air- and ice-frictional is equal to the power used to increase the kinetic energy of center of gravity.
Boer et al. (1989)	65	M:37 F:28	Ice	straights, video images 1500m and 5000m race Hewlett Packard 9874a digitizer Vanguard m-16c motion analyser	Positions of neck, hip, knee, and ankle. Stride of the right leg, push-off angle, speed and stroke frequency. Power stroke	Lack of significant correlations between kinematic variables of technique and performance. It cannot be concluded that hip and knee joint are not important for a proper speed skating technique.
Koning et al. (1991)	7	M	Ice	Video Images, electromyography curve. 10 trials (super grid digitizer)	Push-off forces and electromyographical data	Left leg shows a considerable difference in velocity between the mass center of the body and the ankle.
Hext et al. (2017)	20	M	Ice	5000m relay races: 12 heats, 6 semi-finals and 2 finals. Video Images Bespoke software	Corner exit time. Straight time. Apex block distance. Exit block distance	Team's progression through the 5000m short track relay was found to be dependent on the corner exit speed. Positive effect at slow speeds and a negative effect at faster speeds.
Song et al. (2018)	7	M:4 F:3	Ice	Video Images, curve. 500m race KWON3D 3.1	Kinematic characteristics	Skating as closely as possible to the inside line. Maintain a constant trunk angle. keep the pelvis facing anteriorly
Kruk, E. et al. (2018)	12	M:8 F:4	Ice	5 rounds at constant velocity. Video Images. COP on the blade MYLAPS Timing Services	Measuring forces. Entering the curve, hanging into the curve, leaving the curve and entering the straight. Push-off forces.	The instrumented skate functioned well. Females showed a trend towards applying higher body weight than the males, while skating at imposed lower velocities
Kimura & Yokozawa (2024)	14	F	Ice	Video Images, curve 3000m race Frame-Dias VI, DKH	Centripetal acceleration and kinematic parameters	Centripetal acceleration during the left and right strokes had a significant effect on the curved-section time. In the right stroke, greater centripetal acceleration, greater inward tilting of the body

The results of the Outer Loading test and the Convergent Validity test stage 1 show the performance of the indicators for the variables studied. For the Cultural Preservation (PB) variable, indicators PB1 and PB4 have valid factor loadings of 0.893 and 0.909, respectively. However, indicators PB2, PB3, and PB5 show negative factor loadings and are declared invalid. In the Digital Technology Integration (ITD) variable, only indicators ITD2 and ITD4 are valid with factor loadings of 0.829 and 0.854, respectively, while indicators ITD1, ITD3, and ITD5 are invalid because they contain negative factors. For the Young Generation Interest (MG) variable, indicators MG1 and MG4 are declared valid with factor loadings of 0.915 and 0.897, respectively. However, indicators MG2, MG3, and MG5 are invalid. Finally, for the variable Interests de la generación joven (DS), indicators DS1 and DS4 are valid with loading factors of 0.925 and 0.941, while DS2, DS3, and DS5 are invalid. Overall, these results indicate that a number of indicators need to be revised or replaced to ensure better construct validity in this study. so that this research data needs to be tested for Outer Loading Test Convergent Validity Stage 2.



Characteristics of the Studies

Biomechanics

The crossover technique is commonly described by coaches and experts in manuals and technical papers with biomechanical differences of both legs. The reviewed articles studied the biomechanics of speed skating during the curve section of the track with the variables that influence skaters' performance.

All searched articles were conducted exclusively on ice speed skating except for Boer (1987b) that also studied ISS. The most common goals defined are determined by biomechanics parameters to evaluate and characterise speed skating technique such as push-off angle of both legs, trunk angle, knee angle and their relation with skating velocity (Boer, 1987a; Boer, 1987b; Boer, 1988; Boer & Nilsen, 1989; Koning et al., 1991; Song et al., 2018 and Kimura & Yokozawa et al., 2024). In addition, Boer (1988), Koning et al. (1991) and Kimura & Yokozawa (2024) also proposed to study the stroke power and changes in velocity related with centripetal force generated when skating the curve and Kruk et al. (2018a) studied push-off forces with an instrumented short-track skate. Hext et al. (2017), Song (2018) and Kimura & Yokozawa (2024) approached trajectories and time spent on the curve linked with the straight parts, entering and exiting of the curve.

The data recollecting procedures used on these studies predominantly based on race analyses, including 500 meters (Song, 2018), 3000 meters (Kimura & Yokozawa, 2024) and 5000 meters (Boer, 1987a; Boer, 1988), 1500m and 5000m (Boer & Nilsen, 1989), except for Boer (1987b) that defined a four-trial test protocol, Koning et al. (1991) that established a protocol of ten trial per skater and Kruk et al. (2018a) that analysed skater's performance in five rounds.

The methodology used to study the biomechanics and technique when skating the curve on ISS, must be chosen with criteria and in a way that allows a focused investigation. The mainly approach used on the articles of this research is video-based analysis linked with the right position and distance to the track. Boer (1987a, 1987b, 1988) and Koning et al. (1991) used one frontal and one sagittal camera placed outside the track to measure biomechanical variables (Bolex Paillard and Teledyne DBM 55). More cameras and positioned on different spots were used on other studies like, in Boer, R. W. & Nilsen (1989) with two sets of two Panning cameras each (LOCAM 5 1-02, Angenieux 12) that followed the skater through the inter lap, in Song (2018) with two cameras positioned on the curve exit and two cameras positioned on both straights section of the track (all NEX-FS700, SONY, Tokyo, Japan), in Kruk et al. (2018a) with the skaters being filmed by five cameras (cameras details not specified), one at each end of the straight, one at the inside of each curve and one panning camera at the finish line and in Kimura & Yokozawa (2024) with two stationary cameras on the beginning and end of the curve, onw panning camera on the inside of the curve (all Phantom VEO 410S and MIRO LC111, Vision Research, USA) and in addition, a digital video camera (W870M, Panasonic, Japan) was used to record the skaters during their races from the top row of the spectator stand. On the study of Hext et al. (2017) only one camera (Sony HDR PJ260VE camcorder) was used and was placed at the end of curve. Only Boer (1987a, 1988) refers the distance of the cameras to skater: sagittal camera 18 meters and frontal camera 20 to 30 metres.

For proper and accurate analysis of the video-based data, synchronisation of the cameras was done in various ways. In the studies of Boer (1987a, 1988) synchronisation was made using internal timing lights and timing light generators pulsing at a frequency of 2Hz. Boer (1987b) synchronised both films at the instant of lifting the push-off leg from the ice or floor. Boer, R. W. & Nilsen (1989) synchronised the cameras electronically using the internal LED system as so Kimura and Yokozawa (2024) but with a wireless LED synchroniser. Koning et al. (1991) used telemetered pulses from the force measuring device for the synchronisation of cine film and also push-off force data and electromyography. Kruk et al. (2018a) used a digital start-end pulse to enable synchronisation with external measurement devices and for Song (2018) the cameras were connected with BNC cables, and a sense trigger was used to control recording.

The curve section of the track can be studied on several aspects. In this review, it can be acknowledged biomechanical variables and also trajectories analyses.



As for the variables studied, except for Hext et al. (2017), all the articles studied biomechanical variables. In the studies of Boer (1987a, 1987b, 1988), Boer and Nilsen, (1989) and Koning et. al. (1991), the variables used for left and right push were push-off angles, knee extension and stroke characteristics (time, length, and frequency). In addition, Koning et al. (1991) also studied the angles generated by the tip of the skate shoe, lateral and medial malleolus, hip and neck, and Song (2018) and Kimura and Yokozawa (2024), studied the position of the centre of mass and body's tilt angles using shoulder / pelvis tilt (Song, 2018) and the angle between the vector from the ankle joint to the centre of mass and the z-axis, and also shank tilt (Kimura & Yokozawa, 2024). The study of trajectories was made by Hext et al. (2017) that related it to time spent during the curve and by Kimura and Yokozawa (2024) that related the trajectories used with the push-off forces.

In all the articles, except Boer et al. (1989) and Hext et al. (2017) there is a consistent approach when analysing differences on both push-offs, left and right legs. Boer (1987a, 1987b, 1988) demonstrated that the left leg's push-off angle, knee extension, and stroke duration contribute significantly to work per stroke, a key determinant of velocity and power output. Also, Koning et al. (1991) refers that the extension of the hip, knee and ankle joints of the left leg occurs over a longer period of time and the extension velocities reach higher values earlier compared to the right leg. On Boer and Nilsen (1989) study it was not found difference between biomechanical variables and performance and Hext et al. (2017) studied just the trajectories used and relay exchange.

Another variable studied was skater's inclination inwards and for Kimura and Yokozawa (2024), skaters with a greater centripetal acceleration tilted their bodies further inward during both right and left strokes. Although Song (2018) did not study skater's inclination we can assume relating results, especially maintaining a constant trunk angle with less than 10° of movement, and extending the knee joint at least 160° during push-off and also keeping the pelvis facing anteriorly, and rotating the pelvis appropriately with blade contact and lift-off.

Another crucial variable analysed is the trajectory adopted on the curve. Song (2018) highlighted the importance of skating as closely as possible to the inside line as a way to be faster and Kimura and Yokozawa (2024) regression analysis revealed how directional velocity and curvature radius influenced centripetal acceleration and curved-section times, offering insights into effective techniques for maintaining acceleration throughout the race. For Hext et al. (2017), team's progression through the 5000m short track relay was found to be dependent on the corner exit speed.

Overall, all articles emphasised the importance of a specific pattern that contribute to skating the curve more effectively. The main aspect is the asymmetry between left and right legs, especially on the push-off phase. For Boer (1987a, 1987b, 1988) and Koning et al. (1991) having a high work per stroke is an efficient aspect for a better curve skating. In addition, Koning et al. (1991) refers that electromyographic patterns revealed differences in muscle activation, with the left leg generating more consistent power. Skaters who managed to align their pelvis and trunk consistently (Song, 2018) while maintaining inward tilt and motor adjustments during curves (Kimura & Yokozawa, 2024) were found to perform better in the curve phase.

Precision in push-off mechanics, the dominance of the left leg, inward tilt of the body or the centre of mass, and synchronised movements are identified as core motor patterns for effective curve performance.

Motor Patterns

The motor pattern analysis on the articles researched links biomechanical coordination, neuromuscular adaptation, and stroke efficiency. The integration of high-speed video assessments, inverse dynamics modelling, and force measurement technologies enables researchers to refine training methodologies for elite skaters. Boer (1987a, 1987b, 1988), Boer and Nilsen (1989), Koning et al. (1991), Hext et al. (2017), Song (2018), Kruk et al. (2018), and Kimura and Yokozawa (2024) collectively contribute to advancing motor control research in speed skating, offering valuable insights for optimising technique and performance.

These methodologies, variables, and patterns collectively offer a comprehensive understanding of skating techniques, with each study contributing unique insights into optimizing performance when skating the curve.



Quality assessment and risk of bias

Table 2 presents the quality assessment of the articles included in this study using the Johanna Briggs Institute (JBI) criteria. All articles are classified as cohort studies and each was systematically evaluated according to the 11 methodological criteria defined by the JBI framework.

These criteria are valuable for identifying high-quality observational evidence, ensuring that the included cohort studies adhere to rigorous research standards. The consistent quality scores across studies strengthen the overall robustness and credibility of any systematic review, allowing for more reliable conclusions and evidence-based recommendations.

Table 2. Quality assessment attributed scores.

Artigos / Critérios JB	1	2	3	4	5	6	7	8	9	10	11	Total	Decision
Boer et al. (1987a)	Yes	Yes	Yes	N/A	N/A	Yes	Yes	Yes	Yes	N/A	Yes	11 / 11	Include
Boer et al. (1987b)	N/A	N/A	Yes	N/A	N/A	Yes	Yes	Yes	Yes	N/A	Yes	11 / 11	Include
Boer et al. (1988)	N/A	N/A	Yes	N/A	N/A	Yes	Yes	Yes	Yes	N/A	Yes	11 / 11	Include
Boer et al. (1989)	N/A	N/A	Yes	N/A	N/A	Yes	Yes	Yes	Yes	N/A	Yes	11 / 11	Include
Koning et al. (1991)	N/A	N/A	Yes	N/A	N/A	Yes	Yes	Yes	Yes	N/A	Yes	11 / 11	Include
Hext et al. (2017)	N/A	N/A	yes	No	N/A	Yes	Yes	Yes	Yes	N/A	Yes	11 / 11	Include
Song et al. (2018)	N/A	N/A	Yes	N/A	N/A	Yes	Yes	Yes	Yes	N/A	Yes	11 / 11	Include
Kruk et al. (2018)	N/A	N/A	Yes	N/A	N/A	Yes	Yes	Yes	Yes	N/A	Yes	11 / 11	Include
Kimura and Yokozawa. (2024)	N/A	N/A	Yes	N/A	N/A	Yes	Yes	Yes	Yes	N/A	Yes	11 / 11	Include

Discussion

The importance of the technique is clearly referred in the literature as a very important aspect to a faster and more efficient skating (Bobbert et al., 2002). In fact, slower skaters have a less effective push-off than the faster skaters (Noordhof et al., 2013) and also fatigue can be a major aspect that influences technique (Hettinga et al., 2009). The asymmetry between the left and right leg push-off mechanics, is a factor that significantly influences skater performance (Liu et al., 2024). These findings were also stated by Boer (1987a), that found out that the power P_{fr} was higher ($3.71 \pm 0.24 \text{ w}\cdot\text{kg}^{-1}$) in the elite group than in the trained group ($3.38 \pm 0.24 \text{ w}\cdot\text{kg}^{-1}$), and also that there were more differences in work per stroke (trained group: 94% of the value of the elite group). Same author (Boer, 1987a), stated that the push-off skate lift from the ice at a 154° knee angle. Boer (1987b), concluded that at the hip joint level, the power was $5 \text{ W}\cdot\text{kg}^{-1}$, knee joint, power was $10 \text{ W}\cdot\text{kg}^{-1}$ and effective knee extension range was very small ($115^\circ - 150^\circ$). Boer (1988), established $4.71 \pm 0.99 \text{ W}\cdot\text{kg}^{-1}$ as the mean power output P_c on the curve, Koning et al. (1991), found out that the mean external of joint powers was $P_j 3.69 5 \pm 0.72 \text{ W kg}^{-1}$, the power necessary to overcome air and ice friction is P_j was $3.60 + 0.51 \text{ W kg}^{-1}$, right leg with mean power output of $3.00 + 0.63 \text{ W kg}^{-1}$ and left leg with mean power of $4.38 + 0.48 \text{ W kg}^{-1}$, Noordhof et al. (2013), stated that effectiveness increased significantly, more vertically directed push-off ($F 2.2, 71.4 = 16.6, P < .001$) and velocity decreases progressively ($F 1.6, 51.2 = 28.6, P < .001$) during the 5000m race, Liu et al. (2024) found out that for male skaters, right knee flexion angle was greater than left knee flexion ($p = 0.004$), trunk flexion angle at the left blade landing was greater than at right blade landing ($p = 0.028$), the left leg push-off angle was greater compared to the right leg push-off angle (takeoff: $p = 0.010$; opposite-side landing: $p = 0.020$). For female skaters, left hip flexion angle at the left blade landing was greater than the right hip flexion angle at the right blade landing ($p = 0.040$), trunk flexion angle at the right blade was greater than at the left blade landing ($p = 0.009$), trunk flexion angle at the left blade takeoff was greater than at the right blade takeoff ($p = 0.048$), right knee flexion angle at the right blade takeoff was greater than at the left blade takeoff ($p = 0.032$), range of flexion-extension of the right knee during the right blade push-off was greater than the left knee during the left blade push-off phase ($p = 0.045$) and Bongiorno et al. (2024b) that suggests that the left leg and the right leg plays a different role in generating force and maintaining velocity regarding the curve and as an example of this study, one of the skaters shows co-activation differences between the right side (14.4 versus 18.7) and the left side (20.8 versus 28.4) for the vastus lateralis and biceps femoris. Electromyographic patterns validate this trend, indicating more consistent muscle activation in the left leg (Koning et al., 1991) and more neuromuscular coordination on the right leg (Bongiorno et al., 2024a). There are also differences between the beginning, during and end of the curve as stated by Kruk et al. (2018), that found out that the strokes at the start of the curve are longer than the other two strokes ($ST = 1.12 \text{ s}$ and $ST = 0.99 \text{ s}$ respectively).



The importance of skater's inclination has been studied on straight technique by Kimura and Yokozawa et al. (2022) being a factor for better effectiveness in skating. Song (2018) and Kimura and Yokozawa (2024), corroborates these findings by identifying key postural techniques and inward inclination as main factors for better skating. An effective method to study kinematics is the use of image capturing through fixed cameras as used in Liu et al. (2024), Bongiorno et al. (2022), Kimura and Yokozawa et al. (2022) or Stoter et al. (2020). This method can be particularly efficient if cameras are placed strategically to capture skater's performance on a sagittal and frontal views as Liu et al. (2024), Stoter et al. (2020), Song et al. (2017) and Noordhof et al. (2013, 2014). Methodological considerations in the reviewed studies indicate a reliance on video-based biomechanical analyses. While early studies (Boer, 1987a; Boer, 1987b; Boer, 1988) employed limited camera setups for sagittal and frontal observations, newer investigations incorporated multi-camera synchronization systems to capture finer movement details (Kimura & Yokozawa et al., 2024; Kruk et al., 2018a). The evolution of technological approaches has enhanced the precision of biomechanical assessments, allowing for more refined analyses of stroke mechanics and trajectory optimization. Trajectory is a feature mainly studied on the curve section of the track and, as shown on this review, has also been recognised as a critical determinant of curve efficiency. Skaters who maintain proximity to the inner track line tend to perform better due to minimised distance and improved velocity conservation (Song, 2018). Regression analyses performed by Kimura and Yokozawa (2024) further support the notion that directional velocity and curvature radius influence centripetal acceleration, ultimately impacting skaters' curve-section times. The importance of curve exit mechanics is underscored by Hext et al. (2017), who found that relay performance depended on optimal corner exit speed.

The use of observation methodology in sports has been growing since the beginning of 2000 and it's been developing new methodological tools for investigators, coaches and teachers (Anguera & Hernández-Mendo, 2013). With this methodology investigators have been creating and validating observational systems and instruments to provide new technical features like Francisco et al. (2023) in Judo or Quiñones et al. (2019) in handball. García et al. (2025) used observation methodology to study physical and biomechanical factors of the start until 20 metres skating on inline speed skating. To our knowledge, no observation system exists to study the full curve. The study of patterns has been done mainly on the muscles and group of muscles used on each part of the technique used like Koning et al. (1991) and Bongiorno et al. (2024a). Other studies have been made with the use of speed tests in inline speed skating like Herrera Quiceno et al. (2020), applied a 300 metres time trial on two groups to analyse effects of a learning protocol.

The predominance of small samples introduces selection bias and limits the generalisability of the results. Differences in camera positioning, synchronisation procedures, and testing environments, as well as the fact that the articles have some temporal difference in their publication, implying access to different technologies, can also contribute to measurement bias. Furthermore, the strong predominance of studies conducted on ice introduces a modality bias that restricts the applicability of the results to inline speed skating. In contrast to inline speed skating, speed skating on ice is an Olympic sport, which allows for more developed scientific involvement. However, regarding biomechanics, inline speed skating has a very large gap in scientific study. This difference highlights the need for dedicated research programs focused on the specific mechanics of inline speed skating.

Limitations and practical applications

The reviewed literature highlights the biomechanical intricacies of speed skating during the curve section of the track, with a particular emphasis on the crossover technique. Future research should explore inline skating biomechanics with equal scrutiny to determine if crossover mechanics differ across skating disciplines. Additionally, larger sample sizes and standardised testing protocols would improve the generalizability of results, ensuring that training methodologies can be optimised across various levels of competitive speed skating. Despite these advancements, certain limitations exist. Most studies focus exclusively on ice speed skating, with only Boer (1987b) expanding the scope to inline skating. Additionally, the variability in testing protocols—from controlled laboratory trials to race-based analyses—suggests the need for standardization in experimental conditions to ensure reproducibility of results. The small sample sizes in several studies also limit the generalizability of findings to a broader population of elite skaters.



Future research would benefit from the development of standardised biomechanical protocols, including fixed camera positions, synchronised multi-camera systems, and consistent configurations of the skating phases. Larger sample sizes are essential to improve external validity. The creation of validated observational instruments for curve analysis represents another promising avenue.

Conclusions

This systematic review underscores the biomechanical variables that define speed skating performance during the curve section. The findings suggest that stroke asymmetry, inward tilt, trajectory optimization, and centripetal acceleration are fundamental components of effective curve execution. The integration of multi-camera video analysis and synchronised force measurement systems has further refined the understanding of movement dynamics.

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