Pojskić, H., van den Tillaar, R., Andersson, H. (2024)
Reliability, Validity, and Sensitivity of Spatiotemporal Parameters in Bandy Sprint Skating Using Skate-Mounted Inertial Measurement Units
Applied Sciences, 14(12): 5168
https://doi.org/10.3390/app14125168

applied sciences

MDPI

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Reliability, Validity, and Sensitivity of Spatiotemporal Parameters in Bandy Sprint Skating Using Skate-Mounted Inertial Measurement Units

Haris Pojskic [1,*], Roland van den Tillaar [2] and Håkan Andersson [3]

[1] Department of Sports Science, Linnaeus University, 392 31 Kalmar, Sweden
[2] Department of Sports Sciences, Nord University, 7600 Levanger, Norway; roland.v.tillaar@nord.no
[3] High Performance Centre, 352 46 Växjö, Sweden; hakan.andersson@hpcsweden.com
* Correspondence: haris.pojskic@lnu.se

Abstract: This study aimed to investigate the reliability, validity, and sensitivity of spatiotemporal parameters, during sprint skating, of bandy players. Thirty-two well-trained male bandy players (age: 17.8 ± 1.2 years; height: 1.80 ± 0.06 m; body mass: 75.7 ± 1.2 kg) participated in this study. They performed two 80 m linear skating sprints. To calculate the velocities and obtain glide-by-glide spatiotemporal variables, nine timing gates and two skate-mounted inertial measurement units (IMUs) were synchronized and used. The spatiotemporal variables at each step included the glide time, glide length, double support time, double support length, step length, and step frequency. All the spatiotemporal variables were analyzed separately: averaged over 80 m, during the acceleration, and the maximal steady-state phases. The relative and absolute reliability of the spatiotemporal parameters were good (ICC > 0.70; CV < 10%), except for the step frequency during the steady-state phase. The spatiotemporal parameters showed "good" to "satisfactory" sensitivity during the acceleration phase and whole sprint, and "marginal" sensitivity during the steady-state phase. Content validity was confirmed by a low percentage of the shared variance (17.9–34.3%) between the spatiotemporal parameters obtained during the acceleration and steady-state phases. A "stepwise" regression significantly predicted the steady-state skating velocity from the spatiotemporal metrics obtained during the acceleration [$F_{(5,26)} = 8.34$, $p < 0.001$, adj. $R^2 = 0.62$] and steady-state phases [$F_{(5,26)} = 13.6$, $p < 0.01$, $R^2 = 0.67$]. Only the step frequency obtained in the acceleration phase significantly predicted the maximal skating velocity ($p < 0.01$), while the glide length and step frequency derived during the steady-state phase significantly added to the prediction ($p < 0.01$). In conclusion, the spatiotemporal parameters, obtained by two skate-mounted IMUs, were shown to be reliable and sensitive measures of sprint skating, and they could be used to provide independent information for the different skating phases. The maximal skating velocity could be predicted from the spatiotemporal parameters, with longer gliding and more frequent steps as the most significant determinants.

Keywords: kinematics; acceleration phase; steady-state phase; maximal velocity; glide time and length; double support time and length; step frequency; wearables; accelerometers

Citation: Pojskic, H.; Tillaar, R.v.d.; Andersson, H. Reliability, Validity, and Sensitivity of Spatiotemporal Parameters in Bandy Sprint Skating Using Skate-Mounted Inertial Measurement Units. *Appl. Sci.* **2024**, *14*, 5168. https://doi.org/10.3390/app14125168

Academic Editor: Mark King

Received: 11 April 2024
Revised: 31 May 2024
Accepted: 12 June 2024
Published: 14 June 2024

1. Introduction

Despite being one of the fastest team sports in the world, little is known about skating kinematics in bandy. It is played on a large, soccer-sized ice rink (i.e., 45–65 m × 90–110 m) that enables elite male bandy players to reach high skating speeds of ≈11 m/s [1], even higher than in ice hockey, which is played in a significantly smaller area. Bandy is played in two halftimes of 45 min between two teams of 11 players, who aim to strike the ball using their sticks into the opponents' goal. Players are constantly engaged in bouts of fast-paced skating activities (e.g., acceleration, sprinting, changes of direction) interspersed by short active and passive recovery periods, which reveals the intermittent high-intensity character of the sport [1–4]. During match play, players cover a distance of ≈450 m, while performing high and very high-intensity accelerations and decelerations, which results in ≈2.4 km of very quick and ≈600 m of sprint skating [3]. Moreover, elite bandy players spend ≈21 min in fast (20–25 km/h), ≈7.5 min in very fast (25–30 km/h), and ≈1.2 min in sprint skating (>30 km/h) [4].

Consequently, it is logical to conclude that quick acceleration and skating speed are two of the most important abilities in bandy, required to win ball possession, attack the opponents' goal, and score. Likewise, it was reported in ice hockey, which shares many similarities with bandy, that better acceleration and sprint performance increased the probability of winning [5,6]. Therefore, the accurate and objective evaluation of the glide-by-glide skating technique during acceleration and maximum speed phases could be crucial for performance optimization. The spatial (e.g., glide length) and temporal (e.g., glide time) characteristics of skating are usually measured by stationary, multi-camera 3D motion-capture systems in laboratory settings [7–10]. Although they are very precise and are considered the "gold standard" in kinematic analysis, these systems are often very expensive, require specific procedural knowledge, are not available in every ice sports hall, and do not cover a large testing area, which together reduces their application value [7,11]. This is especially important considering that bandy training and game playing traditionally take place outdoors, with frequent sprint skating over longer distances (e.g., 80–90 m) [1,12].

On the other hand, portable, easy-to-use, and cheap wearable sensors, such as accelerometers and inertial measurement units (IMUs) that integrate several sensors (e.g., gyroscopes and accelerometers), are more preferable alternatives for kinematic analysis of skating technique in field settings. In particular, Stetter et al. [13,14] and Buckeridge et al. [15] validated the estimation of temporal characteristics (e.g., the ice contact time) from five and six consecutive strides using a single 3D accelerometer mounted on a right ice hockey skate. Comparably, Khandan et al. [7] reported high accuracy in the detection and acquisition of both temporal and spatial data during forward skating on a synthetic ice surface using two skate- and one pelvis-mounted IMUs, respectively.

Despite the importance of accurate and objective evaluation of the glide-by-glide skating technique, there is no research on the kinematical analysis of bandy players, and the translation of the findings from ice hockey research to bandy might not be appropriate and sufficient due to rules-based discrepancies between the sports. Specifically, since tackling is not allowed in bandy, which together with a bigger playing area, enables bandy players to accelerate and glide for longer, reaching a higher maximal speed compared to ice hockey players [1,12]. Consequently, to be established in practice, the development of a reliable, sensitive, and valid on-ice measurement method for the analysis of the spatiotemporal characteristics of skating in bandy is warranted.

The reliability concept refers to the reproducibility of measurements in test–retest trials involving the same subjects [16,17]. Usually, it is examined according to both absolute and relative reliability. The first one is evidenced through the analysis of the typical measurement error (i.e., within-subject variation in repeated trials), whereas the latter is examined according to the stability and maintenance of an individual's ranking relative to others in the group after multiple test–retest assessments [18]. Most frequently, it is represented by the interclass correlation coefficient (ICC). Greater reliability suggests better test accuracy and the potential to detect performance changes over time [17,19]. Test sensitivity reflects the measurement's ability to detect a small, but practically significant, change in performance [19]. It is established by comparing the smallest worthwhile change (SWC) and the typical error (TE) of the measurement. A higher SWC than TE implies better test sensitivity [19].

The validity of a test refers to how well it measures what it is intended to measure [16]. There are different types of validity, including face validity, which measures how well a test logically assesses the ability it aims to measure. For example, in the current study, face validity was established by simulating bandy sprints. Content validity, on the other hand, can be measured by statistical analysis that identifies the relationship between kinematic parameters in different sprint phases. This concept is based on the idea that the spatiotemporal parameters of skating are task dependent, that is to say, they change with an increase in skating speed from acceleration to the steady-state phase [15]. The lack of a relationship between the spatiotemporal metrics obtained during the two phases would indicate that spatiotemporal data could be used to provide independent information for the different skating phases. Predictive validity is another important type of validity that is often demonstrated by how sport-specific outcomes (e.g., skating kinematics) can predict sports performance (e.g., skating maximal velocity) [20]. However, it generally receives little attention in research [21].

We are not aware of any other investigations that have reported on the reliability and sensitivity of spatiotemporal data obtained by IMUs during skating sprints. On the other hand, several studies have reported these measurement metrics on spatiotemporal parameters in running [22–25]. However, due to differences in the kinematics between running and skating, caused by the different frictional characteristics of the surfaces on which they are performed, it is not appropriate to translate IMU-derived spatiotemporal data obtained in running to make conclusions about skating. For instance, sprinters try to shorten the ground contact time (≈0.08–0.10 s) during the maximum speed phase, which is not the case in skating, where a longer gliding phase (e.g., contact time ≈ 0.32–0.35 s) is required to achieve and maintain the maximum speed. Moreover, although the concurrent (i.e., reference) validity of spatiotemporal parameters obtained by IMUs has been extensively studied both in running [11,26–29] and skating [7,13,30] activities, less is known about their content and predictive validity.

Therefore, this study aimed to investigate the reliability, validity, and sensitivity of spatiotemporal parameters of sprint skating in bandy using two skate-mounted IMUs. Based on the previous validity studies in ice hockey and speed skating that showed a high level of accuracy concerning the IMUs used [7,13,30], we hypothesized that spatiotemporal parameters would also show acceptable sensitivity and reliability when observed in well-trained bandy players. Moreover, we hypothesized that the spatiotemporal data would show a low percentage of shared variance when observed separately during the acceleration and steady-state phases. We also expected that the spatiotemporal data would have the power to predict the maximal skating velocity.

2. Materials and Methods

2.1. Participants

Thirty-two well-trained male bandy players (age: 17.8 ± 1.2 years; height: 1.80 ± 0.06 m; body mass: 75.7 ± 1.2 kg; BMI: 23.31 ± 2.18 kg/m^2) voluntarily participated in this study. Before the experimental visit, none of the players reported a history of neuromuscular disease or injuries in the previous six months. The players were asked to avoid sleep deprivation, high-intensity training, and tobacco, alcohol, and caffeine for two days before the visit. All participants were fully informed about the procedures, both orally and in writing, and had signed written consent forms (and by their parents if they were under 18 years of age) before participating. This study was conducted in accordance with the latest revision of the Declaration of Helsinki and the current ethical regulations for research and was approved by the Swedish Ethical Review Authority (no. 2022-01550-01).

2.2. Procedure

Between January and March 2022, all testing was conducted indoors to eliminate the influence of weather conditions on the results. The participant's sprint skating profile was tested 60 min after the participants arrived. Body mass was measured using a calibrated scale and body length was measured using a tape measure stuck to the wall. Afterward, three players at a time performed their own preferred warm-up for 15 min, while wearing their regular training gear, to be ready for testing. After the warm-up, the participants were briefed on the testing procedure and a 16 g inertial measurement unit (IMU) integrated with a 3-axis gyroscope was attached on top of the skate on each foot. The IMU had a maximal measuring range of 2000°s^{-1} ± 3% (Ergotest Technology AS, Statthelle, Norway) and a sampling rate of 200 Hz, but was upsampled to 1000 Hz before step detection algorithm processing. After resting for 5 min, each participant performed two maximal 80 m sprint skating attempts with their club in their hand, as in a competition, starting with the club behind the starting line (See Figure 1: Testing procedure). A 5 min rest period was provided between each attempt.

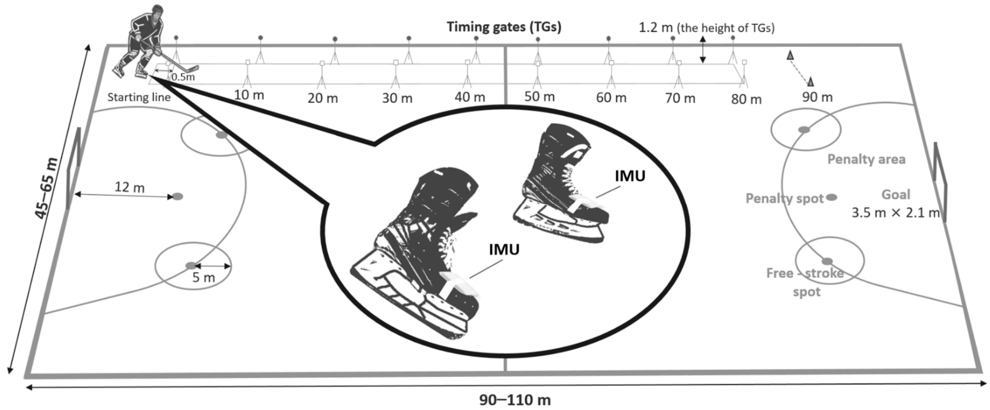

Figure 1. Testing procedure.

Nine timing gates (Ergotest AS, Statthelle, Norway) were placed at 10 m intervals from the start to the 80 m mark, at a height of 1.2 m. The goal was to measure the time taken to cover these distances, and then calculate the average velocities and accelerations per 10 m. The participants started 0.5 m behind the first pair of photocells and were asked to skate for a total of 90 m. The purpose of this was to ensure that they did not finish too early. The participants were encouraged to skate as fast as possible in a straight line.

The IMUs were synced with the timing gates as part of the MUSCLELAB v10.57 system (Ergotest Technology AS, Statthelle, Norway). This allowed the software (Ergotest Technology AS, Statthelle, Norway) to automatically identify skating stride kinematics for each skating step. This methodology has been used in previous studies [7,13,14]. In skating, a stride consists of two phases, support and swing. The support phase can be divided into single and double support phases [31,32]. During both these phases, propulsion takes place as the thigh rotates outward, coinciding with the initial extension of the hip and knee [32]. The time taken for both double and single support is called the glide time, while the total lateral distance covered during both these supports is called the glide length. Step length refers to the lateral distance covered during single support, while the step frequency is calculated by measuring the time elapsed between left and right foot touchdowns. All variables were analyzed separately, as follows: (i) the average over 80 m, (ii) over the first six steps (the acceleration phase), and (iii) over six steps at maximal velocity (i.e., the steady-state phase).

2.3. Statistical Analyses

Descriptive statistics (mean, standard deviation [SD], and range) were calculated for each outcome variable. Before performing parametric statistics, data sets were tested for normality using the Shapiro–Wilk test and by visual observation of normality QQ plots.

The coefficient of variation (CV%), expressed as a percentage, was used to establish absolute reliability [17]. It was calculated as the percentage of the within-subject SD. A CV of <10% was considered to be an acceptable absolute reliability [33]. The relative reliability was determined using the intraclass correlation coefficient (ICC, model 3,k), accompanied by 95% confidence intervals (CIs). Its calculation was based on a mean measurements (k = 2), absolute agreement, and 2-way mixed-effects model [18,34,35]. The following descriptors were used to evaluate the level of reliability for each outcome measurement: "low" (0.20–0.49), "moderate" (0.50–0.74), "high" (0.75–0.89), "very high" (0.90–0.98), and "extremely high" (≥0.99) [35].

Measurement sensitivity was computed by comparing the typical measurement error with the smallest worthwhile change (SWC), both expressed in the measurement scores for each value [17]. The SWC was derived from the between-subject SD multiplied by either 0.2 ($SWC_{0.2}$) [19,36], which is the typical small magnitude effect, or 0.5 ($SWC_{0.5}$), which is an alternate moderate effect [37]. A typical measurement error below the SWC indicated that the measurement sensitivity was "good" and a typical measurement error that was the same as the SWC was rated "satisfactory". If a typical measurement error was higher than the SWC, it was deemed to have "marginal" sensitivity [19,36].

The systematic measurement error was evaluated using paired sample t-tests, assuming no differences between the test and retest mean values. The magnitude-based effect size (d) was calculated to determine the test–retest differences, using the following criteria: <0.20 = "trivial", 0.20–0.59 = "small", >0.6–1.19 = "moderate", >1.2–2.0 = "large", and >2.0 = "very large" differences [38]. Additionally, the paired sample t-tests were used to examine differences in the spatiotemporal variables between the steady-state and acceleration phases.

Pearson's product-moment correlation coefficient (r) was used to examine the association between spatiotemporal measures obtained in the acceleration and steady-state phases. The strength of the correlations was interpreted using the following qualitative descriptors: <0.20 = "very weak", 0.20–0.40 = "weak", 0.41–0.70 = "moderate", 0.71–0.90 = "strong", and >0.90 = "very strong" correlation [39].

Two multiple stepwise regression analyses were used to examine how well the spatiotemporal variables derived during the acceleration and steady-state phases could predict the outcome measure (i.e., skating velocity). The coefficient of determination (R^2) was used to determine the percentage of shared variance between the criterion and the predictors. Before performing the multiple regression calculation, the collinearity between the predictors was checked. The variance inflation factor for most of the predictors was below 2.5, but the variance inflation factor for the glide time showed high multicollinearity (>5) and, therefore, it was excluded from both predictor sets [40]. Statistical analyses were performed using freely available MS Excel 2016 charts and SPSS® 29.0 (IBM SPSS Statistics, New York, NY, USA) for Windows, and the alpha level was set at $p < 0.05$.

3. Results

The Shapiro–Wilk test showed that the data sets for all measures were normally distributed (0.94–0.98; all $p > 0.5$). Descriptive statistics were calculated for all the measured variables, including age and anthropometrics. The sample was shown to be homogenous, with low between-subject variability (CV% < 10%) for all the observed characteristics, except for two spatiotemporal variables, namely the double support time and length (CV% = 12.8–19.1). The paired sample analyses showed higher spatiotemporal values in the steady-state phase than in the acceleration phase ($p < 0.01$), except for the step frequency, which was higher in the acceleration phase ($p < 0.01$) (Tables 1–3). All differences showed a "very large" effect size (d > 2), except the double support time, which showed a "large" effect size (d = 1.5).

3.1. Reliability and Sensitivity

The descriptive and reliability statistics for all the outcome variables are presented separately for the steady-state phase, acceleration phase, and the average over 80 m skating, in Tables 1–3. Only three variables (velocity, double support time, and length), obtained during the acceleration phase, differed statistically between the trials ($p < 0.05$, "trivial" d). There was a 1.6% improvement in the velocity, and a shorter double support time and length (6.2% and 4.6%, respectively) from trial 1 to trial 2. The absolute reliability for all the spatiotemporal variables was shown to be acceptable (CV < 10%), but poorer in terms of the double support time and length, irrespective of the skating phase. The relative reliability for all the outcome variables averaged over an 80 m skating distance was "moderate" to "very high" (ICC = 0.73–0.97). It was "high" to "very high" (ICC = 0.76–0.90) during the acceleration phase and "moderate" to "very high" (ICC = 0.57–0.98) during the steady-state phase for all the variables, except for the step frequency that showed "low" relative reliability (ICC = 0.26). For all the variables, except the glide time, typical error values were lower than <5% of the mean values.

For all the measures obtained during the acceleration phase and as the average over 80 m of skating, the typical errors were lower or equal to their respective $SWCs_{(0.5)}$, showing a "good" to "satisfactory" test sensitivity. The results obtained during the steady-state phase indicated "marginal" sensitivity [TE > $SWC_{(0.5)}$] for the glide time, step frequency, double support time, and length, while they showed "good" sensitivity [$SWC_{(0.5)}$ > TE] for the velocity, glide, and step length (Tables 1–3).

Table 1. Descriptive and reliability parameters for the kinematic variables, on average over the total 80 m distance.

Kinematic Variables	Mean ± SD	Min–Max		$CV\%_{(BS)}$	$CV\%_{(WS)}$	$SWC_{(0.2)}$	$SWC_{(0.5)}$	TE	Sensitivity	ICC (CI95%)
Velocity [m/s]	**8.51 ± 0.33**	**7.53**	**9.21**	**3.86**	**0.73**	**0.06**	**0.16**	**0.05**	**GOOD**	**0.97** (0.94–0.99)
Trial 1	8.50 ± 0.33	7.42	8.99							
Trial 2	8.52 ± 0.33	7.53	9.21							
Glide time [ms]	**402 ± 22**	**345**	**469**	**5.63**	**2.76**	**4**	**11**	**8**	**GOOD**	**0.82** (0.64–0.91)
Trial 1	404 ± 21	364	456							
Trial 2	400 ± 27	344	469							
Double support time [ms]	**72 ± 9**	**49**	**98**	**12.90**	**7.10**	**2**	**5**	**5**	**SATISFACTORY**	**0.73** (0.45–0.87)
Trial 1	73 ± 10	54	106							
Trial 2	71 ± 11	49	98							
Glide length [m]	**3.47 ± 0.21**	**2.96**	**3.87**	**6.04**	**2.85**	**0.04**	**0.10**	**0.07**	**GOOD**	**0.83** (0.66–0.92)
Trial 1	3.48 ± 0.21	2.94	3.88							
Trial 2	3.46 ± 0.24	2.96	3.87							
Double support length [m]	**0.63 ± 0.09**	**0.43**	**0.81**	**13.74**	**7.64**	**0.02**	**0.04**	**0.04**	**SATISFACTORY**	**0.74** (0.47–0.88)
Trial 1	0.64 ± 0.09	0.46	0.90							
Trial 2	0.62 ± 0.11	0.43	0.81							
Step length [m]	**2.83 ± 0.16**	**2.46**	**3.17**	**5.69**	**2.01**	**0.03**	**0.08**	**0.04**	**GOOD**	**0.90** (0.78–0.95)
Trial 1	2.84 ± 0.16	2.46	3.12							
Trial 2	2.83 ± 0.18	2.46	3.174							
Step frequency [step/s]	**3.07 ± 0.17**	**2.71**	**3.51**	**5.50**	**2.32**	**0.03**	**0.08**	**0.06**	**GOOD**	**0.85** (0.69–0.93)
Trial 1	3.05 ± 0.16	2.69	3.34							
Trial 2	3.09 ± 0.20	2.71	3.51							

Legend: ms = milliseconds; SD = standard deviation; Min = minimum value; Max = maximum value; $CV\%_{(BS)}$ = between-subject coefficient of variation; $CV\%_{(WS)}$ = within-subject coefficient of variation; ICC = intraclass correlation coefficient; SWC = smallest worthwhile change; TE = typical error of measurement; CI95% = 95% confidence interval.

Table 2. Descriptive and reliability parameters for the kinematic variables during the acceleration phase.

Kinematic Variables	Mean ± SD	Min–Max		$CV\%_{(BS)}$	$CV\%_{(WS)}$	$SWC_{(0.2)}$	$SWC_{(0.5)}$	TE	Sensitivity	ICC (CI95%)
Velocity [m/s]	**6.18 ± 0.29**	**5.53**	**6.86**	**4.71**	**1.89**	**0.06**	**0.15**	**0.10**	**GOOD**	**0.87** (0.66–0.94)
Trial 1	6.13 ± 0.31 *	5.05	6.85							
Trial 2	6.23 ± 0.31	5.53	6.86							
Glide time [ms]	**367 ± 27**	**302**	**418**	**7.36**	**3.24**	**5**	**14**	**11**	**GOOD**	**0.82** (0.63–0.91)
Trial 1	371 ± 28	315	451							
Trial 2	363 ± 30	302	418							
Double support time [ms]	**63 ± 12**	**37**	**90**	**19.15**	**9.73**	**2**	**6**	**6**	**SATISFACTORY**	**0.77** (0.51–0.89)
Trial 1	65 ± 13 *	38	112							
Trial 2	61 ± 13	37	90							
Glide length [m]	**2.31 ± 0.20**	**1.89**	**2.70**	**8.61**	**3.33**	**0.04**	**0.10**	**0.06**	**GOOD**	**0.88** (0.76–0.94)
Trial 1	2.31 ± 0.19	1.89	2.72							
Trial 2	2.30 ± 0.22	1.88	2.69							
Double support length [m]	**0.41 ± 0.08**	**0.23**	**0.57**	**18.48**	**9.78**	**0.02**	**0.04**	**0.04**	**SATISFACTORY**	**0.76** (0.50–0.88)
Trial 1	0.42 ± 0.08 *	0.24	0.68							
Trial 2	0.40 ± 0.08	0.23	0.57							
Step length [m]	**1.89 ± 0.15**	**1.60**	**2.26**	**8.05**	**2.81**	**0.03**	**0.08**	**0.04**	**GOOD**	**0.90** (0.80–0.95)
Trial 1	1.88 ± 0.15	1.63	2.23							
Trial 2	1.90 ± 0.17	1.60	2.26							
Step frequency [step/s]	**3.32 ± 0.21**	**1.60**	**2.26**	**6.44**	**2.51**	**0.04**	**0.11**	**0.08**	**GOOD**	**0.86** (0.72–0.93)
Trial 1	3.30 ± 0.21	2.95	3.72							
Trial 2	3.34 ± 0.24	2.87	3.80							

Legend: ms = milliseconds; SD = standard deviation; Min = minimum value; Max = maximum value; $CV\%_{(BS)}$ = between-subject coefficient of variation; $CV\%_{(WS)}$ = within-subject coefficient of variation; ICC = intraclass correlation coefficient; SWC = smallest worthwhile change; TE = typical error of measurement; CI95% = 95% confidence interval; * = significantly different from Trial 2, $p < 0.05$.

Table 3. Descriptive and reliability parameters for the kinematic variables during the steady-state phase.

Kinematic Variables	Mean ± SD	Min–Max		$CV\%_{(BS)}$	$CV\%_{(WS)}$	$SWC_{(0.2)}$	$SWC_{(0.5)}$	TE	Sensitivity	ICC (CI95%)
Velocity [m/s]	**10.03 ± 0.45** ¥	**8.57**	**10.87**	**4.47**	**0.78**	**0.09**	**0.22**	**0.06**	**GOOD**	**0.98** (0.95–0.99)
Trial 1	10.05 ± 0.45	8.56	10.76							
Trial 2	10.00 ± 0.45	8.57	10.87							
Glide time [ms]	**433 ± 27** ¥	**377**	**503**	**6.15**	**3.72**	**5**	**13**	**14**	**MARGINAL**	**0.69** (0.37–0.85)
Trial 1	437 ± 28	385	500							
Trial 2	437 ± 28	377	503							
Double support time [ms]	**82 ± 12** ¥	**55**	**115**	**15.06**	**9.79**	**2**	**6**	**8**	**MARGINAL**	**0.57** (0.14–0.79)
Trial 1	84 ± 13	58	115							
Trial 2	80 ± 16	55	114							
Glide length [m]	**4.35 ± 0.32** ¥	**3.56**	**4.98**	**7.24**	**3.79**	**0.06**	**0.15**	**0.14**	**GOOD**	**0.78** (0.53–0.89)
Trial 1	4.39 ± 0.34	3.52	4.92							
Trial 2	4.31 ± 0.35	3.55	4.98							
Double support length [m]	**0.84 ± 0.15** ¥	**0.54**	**1.55**	**18.05**	**9.92**	**0.03**	**0.08**	**0.09**	**MARGINAL**	**0.64** (0.26–0.83)
Trial 1	0.85 ± 0.14	0.57	1.17							
Trial 2	0.83 ± 0.21	0.54	1.55							
Step length [m]	**3.51 ± 0.25** ¥	**2.90**	**4.00**	**7.06**	**3.28**	**0.05**	**0.12**	**0.11**	**GOOD**	**0.79** (0.57–0.90)
Trial 1	3.52 ± 0.28	2.81	4.11							
Trial 2	3.50 ± 0.26	2.89	4.00							
Step frequency [step/s]	**2.89 ± 0.21** ¥	**2.51**	**4.23**	**7.41**	**4.52**	**0.04**	**0.11**	**0.23**	**MARGINAL**	**0.26** (−0.48–0.62)
Trial 1	2.85 ± 0.18	2.38	3.16							
Trial 2	2.94 ± 0.36	2.51	4.23							

Legend: ms = milliseconds; SD = standard deviation; Min = minimum value; Max = maximum value; $CV\%_{(BS)}$ = between-subject coefficient of variation; $CV\%_{(WS)}$ = within-subject coefficient of variation; ICC = intraclass correlation coefficient; SWC = smallest worthwhile change; TE = typical error of measurement; CI95% = 95% confidence interval; ¥ = significantly different from the acceleration phase, $p < 0.01$.

3.2. Content and Predictive Validity

There were positive "moderate" within-measure correlations (r = 0.42–0.62; $p < 0.05$) between the acceleration and steady-state phases. The shared variance of the measures ranged from 17.9 to 37.8% (Table 4).

Table 4. Correlation between the kinematic variables in the acceleration and steady-state phases.

Kinematic Variables	r (CI95%)	% of Common Variance
Velocity (m/s)	0.62 * (0.34–0.79)	37.8
Glide time (ms)	0.46 * (0.14–0.70)	21.4
Double support time (ms)	0.42 * (0.09–0.67)	17.9
Glide length (m)	0.52 * (0.21–0.74)	27.4
Double support length (m)	0.44 * (0.11–0.69)	19.5
Step length (m)	0.46 * (0.13–0.70)	21.2
Step frequency (steps/s)	0.59 * (0.30–0.78)	34.3

Legend: r = Pearson's correlation coefficient; CI95% = 95% confidence interval of r; * = significant correlation, $p \leq 0.05$.

Two "stepwise" multiple regression analyses were run to predict the maximal skating velocity from the spatiotemporal variables obtained in the acceleration and steady-state phases. The first regression significantly predicted the maximal skating velocity, $F_{(5,26)} = 8.34$, $p < 0.001$, adj. $R^2 = 0.62$, with step frequency being the only significant predictor ($p < 0.001$). The second regression model also significantly predicted the maximal skating velocity, $F_{(5,26)} = 13.60$, $p < 0.001$, adj. $R^2 = 0.67$. Only the glide length and step frequency added significantly to the prediction ($p < 0.001$). The glide time was excluded from both models due to the high multicollinearity (variance inflation factor > 5). Table 5 shows the regression coefficients and standard errors.

Table 5. Prediction of maximal skating velocity using the spatiotemporal variables derived from the acceleration and steady-state phases.

	The Acceleration Phase					The Steady-State Phase				
Max Velocity (m/s)	***B***	**SE *B***	**β**	**R^2**	**ΔR^2**	***B***	**SE *B***	**β**	**R^2**	**ΔR^2**
Model				0.62	0.54				0.72	0.67
Constant	−10.97	6.29				−2.19	2.25			
Double support time (s)	0.02	0.04	0.65			−0.01	0.01	−0.14		
Glide length (m)	−13.06	10.55	−5.79			2.19	0.58	1.55 *		
Double support length (m)	11.67	11.07	1.98			−1.45	1.06	−0.49		
Step length (m)	17.45	11.18	5.94			−0.32	0.54	−0.17		
Step frequency (steps/s)	3.55	1.03	1.70 *			1.86	0.41	0.89 *		

Legend: Model = "stepwise" method; *B* = unstandardized regression coefficients; SE *B* = standard error of the coefficient; β = standardized coefficient; R^2 = coefficient of determination; ΔR^2 = adjusted R^2; * $p < 0.001$.

4. Discussion

This study provides several important findings: (1) two skate-mounted IMUs in combination with timing gates can provide reproducible and sensitive data on the spatiotemporal metrics of bandy sprint skating, both during the acceleration and steady-state phases, (2) the spatiotemporal data could be used to provide independent information on the different skating phases, such as the acceleration vs. the steady-state phase, and (3) the most important determinants for predicting the maximal skating velocity from spatiotemporal variables were the step frequency obtained during the acceleration phase and the glide length and step frequency obtained during the steady-state phase.

4.1. Reliability and Sensitivity

Neither the validity nor the reliability of spatiotemporal metrics obtained from skate-mounted IMUs has been extensively studied to date. However, two recent and one older study have shown the application of IMUs to be an accurate and a valid method for identifying spatiotemporal variables in skating, when compared to 3D video analysis [7] and foot pressure sensors [13,30] as reference methods. On the other hand, both the validity [11,26–28] and reliability [22–25] of spatiotemporal data derived from IMUs during running have been widely investigated and, therefore, a comparison with those studies is possible. Previous studies have reported good to excellent relative reliability of spatiotemporal data, obtained during running, using shoe-mounted IMUs. Specifically, Gindre et al. [22] and Koznic et al. [23] reported a high level of reproducibility in running stride kinematics (ICC = 0.70 to 0.99) at different speeds (i.e., 12, 15, 18, and 21 km/h) and on different surfaces (i.e., asphalt, macadam, grass). The findings from the current study corroborate the findings from these studies, evidencing acceptable test–retest reproducibility for all spatiotemporal variables when averaged over an 80 m skating distance (ICC = 0.73–0.97), and when obtained during the acceleration (ICC = 0.76–0.90) and steady-state phases (ICC = 0.57–0.98). Only the step frequency showed "low" relative reliability (ICC = 0.26) during the steady-state phase. This means that the participants' ranking order could be accurately determined, based on all spatiotemporal outcomes in all skating phases, except for the step frequency derived during the steady-state phase [18]. However, the step frequency did not differ significantly between the trials, and its absolute reliability estimated by the CV% (i.e., within-subject variability) was less than 5%, showing good test–retest reliability.

Likewise, the absolute reliability of the spatiotemporal parameters obtained in this study was good (CV < 5%), which is in line with that previously reported in the running studies. Specifically, Gindre et al. [22] reported CVs of 6.5–9.9%, 4.6–5.2%, and 3.9–4.4% for the contact time, aerial time, and step frequency at different running speeds. Comparably, Koznic et al. [23] reported CVs of 1.2–7.3%, 1.2–1.9%, and 0.8–1.0% for the contact time, stride length, and step rate at different running speeds and on different surfaces. The good absolute reliability (i.e., a small amount of within-subject variability) observed in the current study could be attributed to the high proficiency sample (i.e., elite junior bandy players), who could consistently skate in the repeated trials. Only the double support time and length showed worse, but still acceptable, absolute reliability (CV < 10%), irrespective of the skating phase, when compared to the other spatiotemporal metrics. Moreover, only the double support time and length systematically differed from trial 1 to trial 2 during the acceleration phase. Practically, this means that a longer familiarization, an extra testing trial, or the need to average the data from the two trials might be required for an accurate estimate of these specific spatiotemporal metrics [18,41,42]. In addition, the CV% as a type of measurement error might be useful for directly comparing the reliability of spatiotemporal characteristics across different skating activities irrespective of calibration or scaling, the measurement devices used, and the participants tested [17]. In contrast, ICC is a unitless quantitative estimate of between-subject trial-to-trial differences [18].

All the spatiotemporal metrics obtained when the data were averaged and obtained during the acceleration phase, were shown to have satisfactory to good sensitivity [i.e., $SWC_{(0.5)} \geq TE$]. Explicitly, the spatiotemporal variables can be used to detect moderate changes that exceed 0.5 times the metrics' SD, showing "good" measurement sensitivity [19,43]. In practice, it means that if a player, for instance, has increased their glide length after a training intervention for more than SD $\times$ 0.5, the change in performance could be considered real [17]. On the contrary, the glide time, step frequency, double support time, and length derived during the steady-state phase showed marginal sensitivity [i.e., $TE > SWC_{(0.5)}$] and, therefore, any training-based changes in these variables must be taken with caution.

4.2. Content Validity

To establish content validity, the correlations between the spatiotemporal metrics obtained during the acceleration and steady-state phases were examined. The "moderate" correlations (i.e., ranging from 17.9 to 37.8% of the shared variance) suggest that the observed spatiotemporal variables provide independent measures based on the skating phase in which they were acquired. These findings are in line with the idea that spatiotemporal parameters of sprint skating are task dependent, that is to say the skating kinematics are changed with an increase in skating speed from a running-like technique at acceleration to a gliding technique during the steady-state phase [15]. For instance, Stetter et al. [14] showed that accelerometer-derived metrics could be sensitive to the skating phase, with a shorter contact and stride time during the acceleration phase. The results from the current study corroborate this concept, showing a significantly shorter gliding time (367 vs. 433 ms), length (2.31 vs. 4.35 m), double support time (63 vs. 82 ms), and length (0.41 vs. 0.84 m), and step length (1.89 vs. 3.51 m) in the acceleration phase than in the steady-state phase. This was accompanied by a higher step frequency (3.32 vs. 2.89 step/s) and a lower velocity (6.18 vs. 10.03 m/s) during the acceleration phase compared to the steady-state phase.

Based on previous studies, phase-to-phase changes are the result of greater hip rotation and abduction, and knee flexion at ice contact, during the acceleration phase than the steady-state phase [5,9]. These specific joint actions enable a larger stride propulsion and push-off force, which are accompanied by a shorter contact and stride time and higher muscle activation (e.g., the gastrocnemius) in the acceleration phase than in the steady-state phase [14,15,44]. Moreover, the players' center of mass has a larger vertical and a smaller side-to-side oscillation during the acceleration phase than in the steady-state phase [9], which is followed by a decreased step width and an increased glide length as a player transit from the running-like to the gliding phase [9,45,46].

All of these biomechanical and technique adaptations, when transiting from acceleration to maximal steady-state skating, are logical when considering the mechanical properties of the ice surface. Specifically, due to its low friction, players must set their skate blades in an optimal and fixed push-off on-ice position (e.g., with the blade on edge and perpendicular to the movement line) to maximize traction and the reactive force, which in turn enables fast forward propulsion and skating velocities [5,45,46]. After transitioning from running to gliding, the low friction of the ice becomes an advantage because it allows for longer strides, resulting in increased speed [45–47]. Consequently, it is essential to analyze the acceleration phase and steady-state phase separately to gain a complete understanding of skating kinematics and techniques, since the maximum skating speed and acceleration are critical components of bandy.

4.3. Predictive Validity

The current study found that the step frequency during both the acceleration phase and the steady-state phase, along with the glide length obtained during the steady-state phase, were the most important kinematic metrics in predicting the maximal skating velocity. Since there have been no regression models conducted yet to predict the maximum skating velocity from spatiotemporal parameters obtained using skate-mounted IMUs, it is only possible to compare our results with those of studies that aimed to identify biomechanical characteristics that differentiate between high- and low-caliber hockey players, leading to a faster skating performance [5,14,15,48,49].

Specifically, Renaud et al. [5] showed that faster skaters had similar step lengths, but shorter skate contact and double support times, with a higher stride frequency during the skate start. Likewise, Stetter et al. [14] reported a higher skating velocity, stride propulsions, and lower contact time (i.e., higher step frequency) in high-caliber than low-caliber players. Given that power is the product of stride frequency and the amount of force applied on the ice by each stride, logically, a faster forward propulsion and speed could be attained by maximizing the frequency and distance over which the force is exerted [32]. The optimal way to do it is to move the lower-body limbs as far as possible through the range of motion, while keeping a high stride frequency [15,32,49–51]. Previous studies have demonstrated that this can be achieved through high activation of the hip flexors and relaxation of the antagonist muscles (e.g., the gluteus maximus), along with fast and large hip abduction, which together results in a rapid swing phase (i.e., a higher step frequency) and a longer glide [15,48,50,51].

In addition, our study corroborates with the findings by Upjohn et al. [49] regarding the importance of stride frequency in forward skating during the steady-state phase. According to their research, faster skaters could be differentiated from slower skaters based on their stride frequency during the steady-state phase. However, the comparison between our results and theirs may be debatable since they carried out their research on a skating treadmill. Moreover, glide length obtained only during the steady-state phase significantly determined the maximal velocity. This can be attributed to faster skaters having better reactive strength, a larger ankle plantar flexion and knee extension at push-off, and a larger hip range of motion (i.e., increased hip flexion and abduction) and concentric force development during the glide phase [5,15,48,49,52].

Consequently, this could provide them with increased glide length and, thus, a longer distance at which the force is applied. If this is accompanied by a high step frequency, and a faster forward propulsion, ultimately an increase in speed can be expected. Furthermore, it is worth noting that Stetter et al. [14] showed a stronger correlation between stride propulsion velocity and the total sprint time registered during the acceleration phase than that obtained during the steady-state phase, which demonstrates the importance of the acceleration phase in achieving the maximal skating velocity. This is in line with our findings, which showed that while step frequency determines the maximal velocity, a greater contribution was made by the step frequency obtained during the acceleration phase rather than the steady-state phase.

4.4. Limitations

The current study has several limitations that must be acknowledged. First, we did not validate the IMU-derived spatiotemporal metrics against any reference gold standard method for kinematic analysis, such as 3D motion-capture systems, because we wanted to obtain the data over a larger skating distance (i.e., 80 m). Second, neither joint kinematics nor muscle activation were examined, which could potentially provide some additional explanations of the underlying mechanisms that could affect the obtained spatiotemporal metrics, their relationship in different sprint phases, and their power to predict the maximal skating speed. Third, the study did not compare male and female players, playing levels, and positions, which could show whether the IMU-derived spatiotemporal metrics had appropriate discriminative validity. Furthermore, the study included only male bandy players, which might limit the potential to generalize the findings from the study to female players. However, future studies should be designed to explore the abovementioned limitations.

5. Conclusions and Practical Application

This study was the first to investigate spatiotemporal parameters in bandy sprint skating. The study showed that spatiotemporal parameters obtained by two skate-mounted IMUs were reliable and sensitive measures of sprint skating, and they could be used to provide independent information for the different skating phases. The step frequency during both the acceleration phase and steady-state phase, along with the glide length obtained during the steady-state phase, were the most important kinematic metrics in predicting the maximal skating velocity. The step frequency during the acceleration phase was shown to be more important than the step frequency during the steady-state phase in attaining the maximal speed.

Using two skate-mounted IMUs is a simple and cost-effective way for coaches to receive instant feedback on the skating technique. This method can be used not only in limited skating spaces, as with 3D motion-capture systems, but also over the entire sprinting distance (e.g., 80 m). Bandy coaches and practitioners should be informed that after adequate familiarization and self-selected warm-up, only two test trials are necessary for the accurate estimation of the spatiotemporal metrics in each skating phase. Since the method showed satisfactory to good sensitivity to detect small to moderate changes in spatiotemporal variables, it is recommended to monitor the skating technique and improvements over time.

Given that the spatiotemporal parameters of sprint skating are task dependent, that is to say the skating kinematics are changed with an increase in the skating speed from a running-like technique at acceleration to a gliding technique during the steady-state phase, their independent analyses and development are warranted. Specifically, coaches should aim to optimize training strategies by emphasizing the step frequency (i.e., short contact time, fast swing of the lower limbs) in the acceleration phase and the glide length in the steady-state phase without compromising the step frequency. The first one might be improved by training methods that involve fast eccentric muscular contractions (e.g., plyometrics, assisted sprints), while the latter by using a slower concentric contraction with higher force output (e.g., lower-body strength, resisted sprints). However, future training studies are required to examine these strategies and their effects on the skating technique by bandy players.

Author Contributions: Conceptualization, H.P. and R.v.d.T.; methodology, H.P.; validation, H.P.; formal analysis, H.P.; investigation, H.A. and R.v.d.T.; data curation, H.A.; writing—original draft preparation, H.P.; writing—review and editing, H.P., R.v.d.T. and H.A.; visualization, H.P.; supervision, R.v.d.T.; project administration, H.P., R.v.d.T. and H.A.; funding acquisition, H.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Swedish Bandy Association.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Swedish Ethical Review Authority (no. 2022-01550-01).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors would like to thank the players for their participation in the study and the coaches for their positive attitude toward the study.

Conflicts of Interest: The authors declare no conflicts of interest.

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