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Influence of expertise level on techniques of applying top and back spins in cue sports

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Abstract

This study compared the kinematics of upper body and cue stick among players of various skill levels when performing back spin and top spin shots. Twenty-eight male cue sports players were assigned to the novice (n = 10), intermediate (n = 9), or skilled groups (n = 9). The back spin and top spin tests were administrated while kinematic data were recorded using a 3D motion capture system. The results revealed greater upper limb joint ranges of motions (all $p < 0.05$), maximum angular velocities (all $p < 0.05$), and cue tip speed in the back spin than top spin shots ($p < 0.001$). None of joint kinematic or shot performance variables investigated was significantly different among the three skill levels (all $p > 0.05$). For the head movement, the novice group exhibited greater anteroposterior displacement than the skilled group ($p = 0.020$). In conclusion, except for the head movement, the upper body and cue stick kinematics did not significantly differ among players with varied skill levels. Greater joint ranges of motions and angular velocities were required to generate a faster cue tip speed for the back spin shots when compared with the top spin shots.

Keywords: billiards, pool, kinematic, range of motion, angular velocity

Introduction

Cue sports are a variety of popular games played with a cue stick, for example, billiards (e.g., 8-ball, 9-ball, and 10-ball), and snooker. Previous studies have applied 2D video analyses to evaluate the shot performance by measuring the ball movements on the snooker/billiards table (Chung et al., 2014; Haar et al., 2020, 2021; Pan, Komar, & Kong, 2021; Pan, Komar, Sng, et al., 2021). While the physics behind cue sports has been well studied (Jankunas & Zare, 2014; White, 2017), biomechanical research on the human movements are rather sparse (Haar et al., 2020; Kong et al., 2021; Kornfeind et al., 2015). Kornfeind and co-workers (2015) described the 3D kinematics of the cue stick in 20 highly ranked European players when performing 18 predefined, such as draw shot (back spin), follow shot (top spin), stop shot, and break shot. They found that compared with the break shot, other shots came with relatively lower cue stick accelerations at impact. In snooker, a case study on one elite player (Kong et al., 2021) revealed similar upper limb kinematics, ground reaction forces, and centre of pressure patterns across five different types of shots during the cueing movement. Another study on billiards profiled the joint kinematics of the learning progress in beginners who had little or no playing experience (Haar et al., 2020). The authors found that right-handed players' right shoulder mainly contributed to the cueing movement while other joints involved less. These earlier studies provided descriptive data of various types of shots which can serve as useful references for players and coaches. However, the lack of biomechanical comparison between players of various skill levels makes it difficult to identify the characteristics associated with skilled performances. Thus, it is of interest to compare the techniques employed by skilled and less-skilled players when executing cue sports shots.

In the study on billiards by Haar and co-workers (2020), great angular velocities were reported for shoulder abduction/adduction and internal/external rotation. However, anecdotal coaching guidelines emphasised that skilled players should keep the body fixed during the cueing movement (Leider, 2010; Pejcic & Meyer, 1993). Hence, the authors attributed the unexpected obvious shoulder movements to the participants being beginners (Haar et al., 2020). On the other hand, postural variation was observed in skilled performance when executing precision tasks (Arutyunyan et al., 1968, 1969; Müller & Sternad, 2009; Serrien et al., 2018). In these precision tasks, functional variability was reflected by higher postural variation (i.e., higher range of motion for joints or more joints involved) that allowed for continuous compensation between joints in order to maintain pointing/aim stability (Arutyunyan et al., 1968, 1969). In other words, higher variability is meant to increase robustness of the performance. For instance, in air pistol shooting, which requires high level of precision, postural variations have been shown to help maintain stance stability (Arutyunyan et al., 1968, 1969). In addition, it is not necessary for elite archers to minimise their body movements during aiming to stabilise the orientation of the arrow (Serrien et al., 2018). It is currently unclear whether fixed or varied body stabilisation strategies are desirable for precision tasks in cue sports.

Applying spins on the cue ball is a common strategy to park the cue ball at an appropriate position for the next shot. Back spin shots, which require the player to hit the cue ball below its equator, can produce reverse spins and draw back the cue ball after collision with the object ball. When striking the cue ball above the equator as seen in top spin shots, the cue ball continues running forward after hitting the object ball. Skilled players can precisely control the amount of the spin applied to regulate the end position of the cue ball. Across different types of shots in cue sports, there is essentially one primary cueing movement which usually consists a few practice swings and a final stroke (Kong et al., 2021). To conduct different spin shots, players might adopt different techniques to deliver the cue stick in order to manipulate the speed and height of the cue tip at impact. Hence, studying the upper body kinematics in different spin shots can shed light on understanding cue sports techniques and provide valuable information for coaches, scientists, and players. This study aimed to examine the influence of expertise level on the upper body and cue stick kinematics during back spin and top spin shots. It was hypothesised that 1) the kinematics of the upper body and cue stick would differ among cue sports players of different skill levels, and 2) the kinematics would differ between the top spin and back spin shots.

Materials and Methods

Participants

This present study was approved by the Nanyang Technological University Institutional Review Board (Protocol Number: IRB-2019-05-013). All methods of this study were performed in accordance with the Declaration of Helsinki. Participants provided written consent to participate in the study. A priori power analysis shows that at least 27 participants (9 in each group) are required ($\alpha = 0.05$, effect size $f = 0.333$, power = 0.80). The effect size f was calculated from a partial Eta-squared of 0.1 (medium effect size for two-way Analysis of Variance). Twenty-eight male participants (25 were right-handed, 3 were left-handed) of various skill levels were recruited, ranging from recreational players to national team athletes. All of them had at least one year playing experience and were active cue sports players during the time of this experiment. The exclusion criteria were that participants 1) were injured within 3 months of the study, 2) had surgery history to the shoulder, elbow, wrist, or hand, or 3) were experiencing any pain or discomfort when playing cue sports (Pan, Komar, & Kong, 2021).

Participants were required to warm up on the 9-ball pool tables for approximately 10 minutes using a new set of pool balls (diameter: 57.2 mm, Cyclop ZEUS Tournament TV set, Xinzhan Co., LTD, Shanghai, China). After that, a 15-ball test was conducted to examine their overall skill levels (Pan, Komar, & Kong, 2021). Participants were instructed to pot as many as they can consecutively in one single visit with the 15 object balls lined up in the middle line of the pool table. In each trial, the actual number of balls potted was used to indicate the performance. Hence, the total number in the best 2 out of 3 trials (maximum number was $2 \times 15 = 30$) was used, and the participants were assigned to novice (N, n = 10), intermediate (I, n = 9), or skilled (S, n = 9) groups (Table 1).

Table 1. Participants' characteristics of the three groups.

	Novice (N, n = 10)	Intermediate (I, n = 9)	Skilled (S, n = 9)	*p*	η^2_p	*post-hoc*		
Age [years]	25.8 (2.5)	23.4 (3.6)	29.1 (10.8)	0.193	0.117			
Height [cm]	172.5 (5.0)	174.6 (6.8)	171.2 (6.3)	0.503	0.053			
Body mass [kg]	68.8 (10.2)	74.0 (14.4)	69.0 (13.2)	0.609	0.039			
Experience [years]	3.8 (4.0)	4.9 (3.0)	11.4 (8.6)	0.089	0.280			
Balls potted	5.4 (2.3)	12.1 (1.9)	21.6 (4.5)	**< 0.001***	0..838	N<I	N<S	I<S

Balls potted refers to the number of balls potted in the 15-ball test (sum of best 2 out of 3 trials). Significant difference ($p < 0.05$) is shown in bold text and indicated by an asterisk.

Experimental procedures

Two types of 9-ball shots, including the back spin and top spin tests, were adopted from a previous study (Pan, Komar, & Kong, 2021) and conducted in the present study. Familiarisation and practices were allowed prior to the tests. Participants performed 10 successful trials, with the object ball potted into the middle pocket, in each type of shot. If the participants failed to pot the object ball, they were required to repeat the trials until achieved 10 successful trials. In the back spin test, an object ball (red in this schematic representation, Figure 1) was placed at specific spot which can be determined by the 'diamonds' at the pool table cushions. Back spin was applied on the cue ball, which was originally set at the centre of the head string, when potting the object ball. Due to the reverse spin, the cue ball should return to the target represented by a piece of paper (7.5 cm × 5.3 cm); an error distance was measured as the absolute distance between the actual end position of the cue ball and the target centre if the participant failed to do so. In the top spin test, the cue ball was expected to follow the object ball to roll forward upon impact and park at the target in front (Figure 1); an error distance was obtained where necessary.

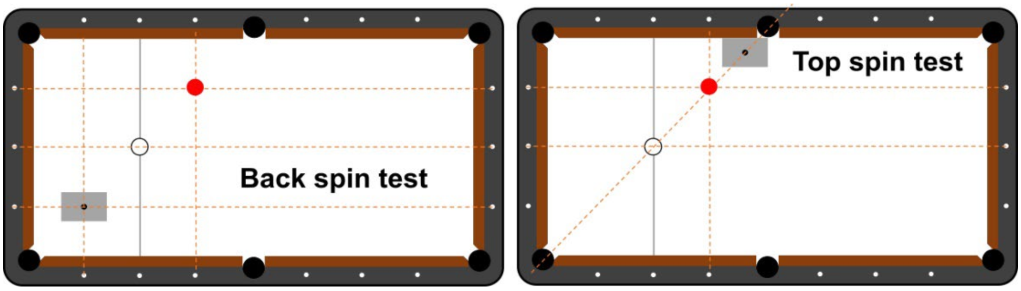

Figure 1. Schematic representations of the back spin and top spin tests. In both tests, a cue ball (white) and an object ball (red) were used. Participants were required to pot the object ball and apply appropriate spin onto the cue ball such that the cue ball can travel and stop at the target, which was represented by a piece of paper (grey).

Data acquisition

In order to measure shot performance, a digital camera (30 Hz, model EX-100, Casio Computer CO., LTD, Tokyo, Japan) was used to record the ball positions on the pool table for each shot. To facilitate the kinematic data acquisition, 24 passive retro-reflective markers (14 mm) were placed on the upper body of the participant, alongside 3 markers on the cue stick (Figure 2). The 24 markers included 4 markers on the head (FHD, BHD, RHD, LHD), 4 on the trunk (STRN, XIPH, C7, T8), 4 on the pelvis (RASI, LASI, RPSI, LPSI), 10 on the bilateral acromion process (RSHO, LSHO), medial epicondyle (RELM, LELM), most caudal-medial point on ulnar styloid (RWRU, LWRU), most caudal-lateral point on radial styloid (RWRR, LWRR), and 3rd metacarpal head (R3MC, L3MC), and 1 on the lateral epicondyle (RELL/LELL) and 1 on the 5th metacarpal head (R5MC/L5MC) for the cue-wielding arm only. Three markers were placed at the cue tip, cue stick middle, and butt, respectively. An 8-camera motion capture system (Vicon MX, Oxford Metrics Ltd., Oxford, UK) was used to record the ball and participant's upper body kinematic data (joint angles, angular velocities) at 250 Hz. The origin of the coordinate system was set at the centre of the bottom cushion. The mediolateral direction was defined as parallel to the bottom cushion, and anteroposterior direction was perpendicular to the bottom cushion.

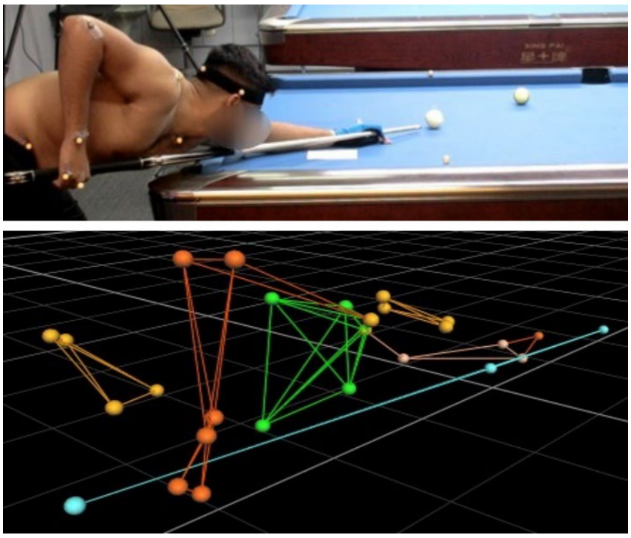

Figure 2 Example of one participant executing shots with retro-reflective markers fixed on the upper body and cue stick.

Data analyses

To analyse the shot performance, an error distance was measured with the software Kinovea (version 0.8.27, Kinovea, Bordeaux, France) (Pan, Komar, & Kong, 2021). A smaller error distance indicates better shot performance, and vice versa. A custom upper extremity model was built comprising the pelvis (CODA model; RASI, LASI, RPSI, LPSI), trunk (STRN, XIPH, C7, T8), head (FHD, BHD, RHD, LHD), and bilateral upper arms (RSHO, RELM, RELL; LSO, LELM, LELL), forearms (RELM, RELL, RWRR, RWRU; LELM, LELL, LWRR, LWRU), and hands (RWRR, RWRU, R3MC, R5MC; LWRR, LWRU, L3MC, L5MC) following the methods provided by Gates et al. (2016) using Visual3D (v6.01.36, C-Motion, Germantown, MD, USA). Raw kinematic data were low-pass filtered using a fourth-order Butterworth filter at the cut-off frequency of 10 Hz, which was determined by the results of the residual analysis (Kong et al., 2021; Winter, 2009). Kinematics of the shoulder, elbow, and wrist of the cue-wielding arm, as well as the cue stick were obtained. Joint angles were defined and calculated following the recommendation of International Society of Biomechanics (ISB) (Gates et al., 2016; Wu et al., 2005). In each shot, the negative elevation of shoulder, elbow flexion/extension, and wrist abduction/adduction were obtained (Gates et al., 2016). One direction was selected for each joint since the movement in these directions directly associate with the cue stick delivery. Positive shoulder angles and angular velocities represent shoulder elevation; negative values represent shoulder negative elevation. Positive elbow angles and angular velocities represent elbow flexion; negative values represent elbow extension. Positive wrist angles and angular velocities represent wrist abduction; negative values represent wrist adduction. Cue stick angle was computed as the angle between the cue stick and the pool table (horizontal plane) at impact (Kornfeind et al., 2015).

There is primarily only one cueing movement in cue sports, which contains a few practice swings and one final stroke. For the final stroke, based on the position of the cue tip in the anteroposterior component (Figure 3), five key moments can be identified: a) start of back swing, b) end of back swing, c) start of forward swing, d) impact, and (e) end of follow through (Kong et al., 2021). Cue stick angle, cue tip height, and cue tip speed at ball-cue tip impact (key moment d) were identified. The ranges of motions (ROM) of upper limb joint angles were obtained from the start of forward swing to the end of follow-through (from key moment c to e, shaded area in Figure 3), as this phase directly contributes to cue tip speed and position. The maximum angular velocities, which were the maximum values of the angular velocities, were also extracted from this phase. To investigate the head movement, the displacement of a marker placed above participants' right ear was obtained from the same phase. It was defined as the difference between the maximum and minimum marker coordinates in the mediolateral, anteroposterior, and vertical components. Similarly, the displacement of the marker fixed on the 8th thoracic vertebra (T8) was identified to assess the trunk movement.

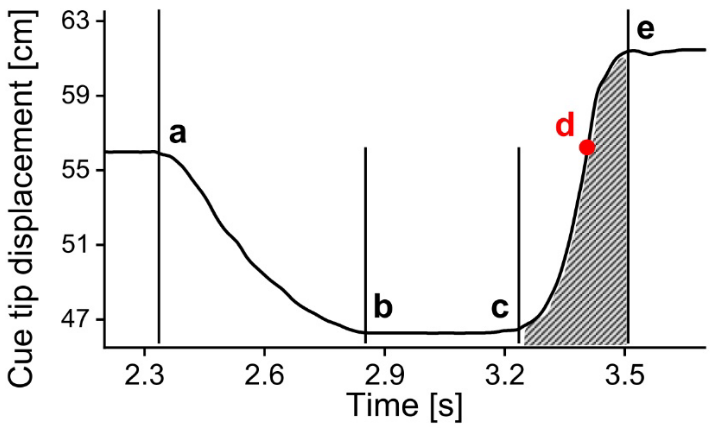

Figure 3 Five key moments [a (start of back swing), b (end of back swing), c (start of forward swing), d (impact), and e (end of follow through)] determined by the anteroposterior displacement of the cue tip in the final stroke. A greater cue tip displacement value indicates cue tip being in a more forward position, and vice versa.

Statistical analyses

Data are expressed as mean (standard deviation). The data were imported into JASP (version 0.14.1; JASP Team, 2020) statistical software for analyses. To compare the shot performance (error distance) among the three groups, a one-way analysis of variance (ANOVA) was conducted. A mixed-model ANOVA (2 Tests × 3 Levels) was performed to compare the kinematic data of the three groups between the back spin and top spin tests. The within-participant factor was Test (back spin shot versus top spin shot), while the between-participant factor was Level (novice, intermediate, skilled). When deviations from sphericity occurred, *p* values were corrected using Greenhouse-Geisser epsilon correction of the mean epsilon was lower than 0.75. When the mean epsilon was above 0.75, Huynh-Feldt correction was applied. Bonferroni adjusted *post-hoc* comparisons were performed where necessary. The effect size for partial Eta-squared (η_p^2) was interpreted as small ($0.01 \leq \eta_p^2 < 0.06$), medium ($0.06 \leq \eta_p^2 <$

0.14), or large ($\eta_p^2 \geq 0.14$) (Lakens, 2013). All statistical tests were set at the 0.05 level.

Results

According to the results of one-way ANOVA, no significant between-group differences were found in either the back spin (p = 0.086) or top spin shots (p = 0.388). In the back spin shot, the novice, intermediate, and skilled groups showed the error distances of 44.1 (24.3), 31.1 (16.3), and 26.1 (5.2) cm, respectively; the error distances were 12.8 (5.5), 9.9 (2.6), and 11.7 (4.7) cm, respectively in the top spin shot. Concerning the kinematic variables, the results of two-way ANOVA showed that there was a significant main effect of Test (all $p < 0.001$, Table 2) for cue stick angle, cue tip height, and cue tip speed. The back spin test was characterised by greater cue stick angle, higher cue tip speed and lower cue tip height when compared with the top spin test. However, there was no significant main effect of Level (all $p > 0.05$), reflecting similar kinematics across players of all skill levels. In addition, no significant interaction effect was found between the Test and Level (all $p > 0.05$).

Table 2. Comparisons of cue stick and upper limb joint kinematics among the three groups in the back spin and top spin tests.

				Level		Test		Interaction	
		Back spin	Top spin	*p*	η^2_p	*p*	η^2_p	*p*	η^2_p
Cue stick									
Cue stick angle [°]	N	6.1 (2.1)	4.0 (0.4)	0.260	0.155	**<0.001***	0.891	0.444	0.083
	I	5.1 (0.8)	3.9 (0.4)						
	S	5.5 (0.7)	4.0 (0.4)						
Cue tip height [cm]	N	2.1 (0.4)	4.0 (0.4)	0.221	0.172	**<0.001***	0.995	0.529	0.076
	I	1.9 (0.3)	3.9 (0.4)						
	S	1.8 (0.3)	4.0 (0.4)						
Cue tip speed [m/s]	N	3.3 (1.5)	1.0 (0.1)	0.492	0.066	**<0.001***	0.953	0.532	0.053
	I	3.0 (0.3)	1.0 (0.1)						
	S	2.8 (0.1)	1.0 (0.1)						
Range of motion [°]									
Shoulder	N	8.8 (5.0)	4.8 (6.0)	0.959	<0.001	**0.015***	0.543	0.054	0.305
	I	8.1 (5.0)	5.8 (4.0)						
	S	11.6 (8.1)	2.4 (1.8)						
Elbow	N	57.4 (21.7)	26.1 (26.8)	0.330	0.130	**<0.001***	0.886	0.139	0.219
	I	60.0 (10.5)	30.3 (23.7)						
	S	57.0 (10.4)	9.9 (16.5)						
Wrist	N	13.4 (5.9)	4.5 (4.7)	0.209	0.178	**<0.001***	0.847	0.448	0.096
	I	11.6 (3.4)	7.2 (6.5)						
	S	10.3 (5.4)	2.3 (2.9)						
Maximum angular velocity [°/s]									
Shoulder	N	46.3 (39.6)	22.4 (12.0)	0.112	0.274	**0.008***	0.610	**0.042***#	0.397
	I	52.5 (40.2)	26.3 (18.3)						
	S	102.1 (75.1)	18.2 (11.4)						
Elbow	N	363.6 (96.7)	81.9 (71.5)	0.131	0.224	**<0.001***	0.948	0.677	0.048
	I	396.9 (96.1)	119.6 (112.5)						
	S	354.2 (122.4)	27.7 (38.3)						
Wrist	N	134.8 (36.6)	35.4 (26.9)	0.078	0.273	**<0.001***	0.907	0.332	0.129
	I	116.8 (29.7)	54.5 (53.7)						
	S	105.2 (41.2)	15.5 (18.8)						

N denotes the novice group. I denotes the intermediate group. S denotes the skilled group. Shoulder denotes shoulder negative elevation. Elbow denotes elbow flexion/extension. Wrist denotes wrist abduction/adduction. Significant difference ($p < 0.05$) is shown in bold text and indicated by an asterisk. # denotes significant differences between skilled players performing the back spin tests than other 5 conditions according to the Bonferroni adjusted *post hoc* comparisons (all $p < 0.05$).

For most joint ROM and maximum angular velocities in the cue-welding arm, there was no significant main effect of Level (all $p > 0.05$, Table 2) while a significant main effect of Test (all $p < 0.005$) was identified with all values greater in the back spin test than the top spin test. Only for the maximum angular velocity in shoulder negative elevation, there was a significant interaction effect of

Level × Test (p = 0.042, η^2_p = 0.397). *Post hoc* comparison revealed that skilled players performed the back spin test with higher shoulder angular velocity than the other 5 conditions (all p < 0.05).

For anteroposterior head displacement (Figure 4 a to c), there was a significant main effect of Level (p = 0.020, η^2_p = 0.466) with the novice group exhibiting greater displacement than the skilled group (mean difference = 0.4 cm, 95% confidence interval [0.1, 0.6] cm). In both mediolateral and vertical head displacements, there was a significant main effect of Test (p = 0.031 and 0.016, respectively) with greater displacement in the back spin test than the top spin test. Regarding the trunk movement, the back spin test was characterised by greater displacements than the top spin test in all three directions (all p < 0.05, Figure 4 d to f). There was no significant difference among the three groups in any trunk movement variables (all p > 0.05).

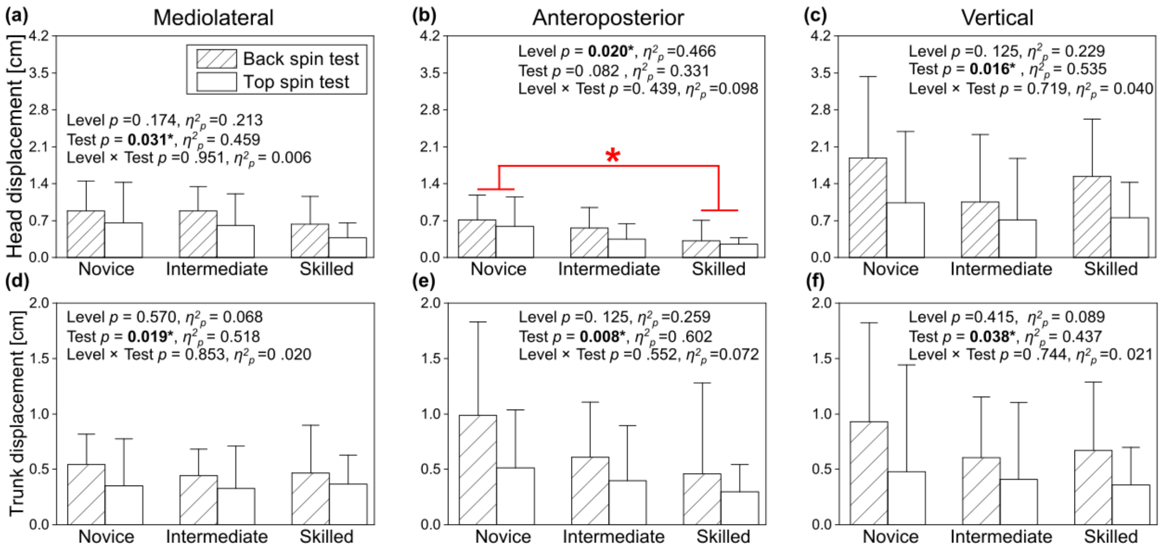

Figure 4. Comparisons of head and trunk displacements among the three groups in the mediolateral, anteroposterior, and vertical components when executing the back spin and top spin tests. The error bar represents group standard deviation. Comparisons were assessed using two-way ANOVA and Bonferroni post-hoc test. The significant *post-hoc* difference between the novice and skill groups is indicated by an asterisk in the head movement in the anteroposterior component.

Discussion and implications

This study compared the kinematics of upper body, cue stick, and shot performance among players of various skill levels when performing the back spin and top spin tests. The cue-wielding arm, trunk, and cue stick kinematics were not significantly different among the novice, intermediate, and skilled groups. Greater joint ROM, maximum angular velocities, cue tip speed, and cue stick angle were observed in the back spin shots compared with the top spin shots for all three groups. During the cueing movement, the novice group showed greater magnitudes of head movements in the anteroposterior direction than the skilled group. No significant differences in shot performance were observed among the novice, intermediate, and skilled groups in either the back spin or top spin shots.

The first hypothesis that the kinematics of the upper body and cue stick would differ among the three groups with various skill levels is not supported by the results of the current study. It is somewhat surprising that there were no significant joint ROM differences among the novice, intermediate, and skilled players. Since the shoulder is supposed to be kept fixed during the cueing movement according to high level coaching and training content (Leider, 2010; Pejcic & Meyer, 1993), one should not expect great shoulder ROM or angular velocities, in particular for skilled players. In the present study, the maximum angular velocity in shoulder negative elevation ranged from 18.2 to 102.1°/s when performing the top spin test (Table 2). The maximum shoulder angular velocities were much lower than those reported by Haar and co-workers (approximately 86 to 229°/s in all three directions) although their test did not require great cue tip speed or strong spins (Haar et al., 2020). This discrepancy in results could be due to the difference in participants' skill levels. Indeed, in the current study, all participants had at least one year playing experience while those in the study by Haar and co-workers had no or very little experience in playing billiards (Haar et al., 2020). The playing experience of the participants in the present study may also explain the lack of between-group differences. Significant kinematic differences were only identified in the shoulder maximum angular velocities according to the *post hoc* analysis (Table 2), which showed that the skilled group had the greatest maximum angular velocities when performing the back spin tests compared with other conditions, although their shoulder ROM was relatively small and similar. This could be because of the greater cue tip speed required in the back spin test than in the top spin test, and can be explained by the leading joint hypothesis (Dounskaia, 2005), which states that the leading joint (shoulder in the cueing movement) generates powerful interaction torques at the subordinate joints (elbow and wrist). However, less skilled may be unable to utilise the shoulder to generate powerful interaction torques at the elbow and wrist. Generally, cue stick and cue-wielding arm kinematics did not show significant difference among the three groups. It is possible that with one year of practice, players would have grasped the basic techniques of performing back spin and top spin shots and therefore no substantial differences in the kinematic patterns were found. In addition, while the kinematics of the independent joints were not different among the players, inter-joint coordination may vary across skill levels. Future studies could further investigate the joint coordination strategies of players with different skill levels rather than joint kinematics in isolation.

Pertaining to how cue sports players stabilise their body when executing the cueing movements, this study examined the head and trunk displacements (Figure 4). Greater head movement in the anteroposterior direction was found in the novice group compared with the skilled group (Figure 4 b). This is in line with the coaching guidelines stipulating that skilled players were able to fix the body while only allowed the elbow and wrist movements to deliver the cue stick (Leider, 2010; Pejcic & Meyer, 1993). This result is contrasting with the concept of 'postural variations' postulating that high level athletes can adopt varied body postures to maintain stance stability (Arutyunyan et al., 1968, 1969). In other precision sports, postural variations were considered promising (Arutyunyan et al., 1969; Serrien et al., 2018) and ubiquitous due to the inherent dynamics of the human body (Kantz & Schreiber, 2004). The flexibility offered by varied body postures provides advantages when the participant is dealing with a precision task (Latash et al., 2002). Observations from the present study showed that skilled cue sports players did not move their body much during the cueing movement as reflected by the small magnitude in head and trunk displacements. Interestingly, postural variations represented by greater head displacement was identified in novice cue sports players instead of more skilled players had smaller magnitudes of head movements. According to common coaching guidelines, greater upper body displacement of novices may impair stance stability and shooting performance and the cue tip could not strike on the correct position on the cue ball (e.g., lower part in back spin shots and upper part in top spin shots). Hence, fixed body was employed by skilled players in cue sports. In the abovementioned studies on air pistol shooting (Arutyunyan et al., 1969) and archery shooting (Serrien et al., 2018), fine finger moves in small magnitudes were primarily involved and varied body postures could compensate the stance stability. However, during the cueing movement which requires large magnitude of elbow and wrist movements, the other body parts should keep still for better stance stability. Furthermore, air pistol shooting and archery athletes stand only on their feet, while in cue sport, the bridge hand was placed on the pool table for the purpose of supporting the cue stick. The players' body weight being partially distributed on the pool table may contribute to providing stance stability. Owing to the differences in movement nature and stance posture between cue sports and other precision sports, this present study does not support the concept of 'postural variations'. Cue sports players are recommended to minimise non-relevant head movements when delivering the cue stick.

The second hypothesis is verified as significant differences in the cue-wielding arm and cue stick kinematics were observed between the back spin and top spin tests. When performing the back spin shots, the cue tip was lower than that in the top spin shots (mean difference = -2.0 cm, 95% confidence interval [1.9, 2.1] cm). By striking the cue ball on a precise position, the correct type of spin (i.e., back spin if hitting below the equator, and top spin if hitting above the equator) can be produced. By observing the cue ball trajectory upon impacting the object ball, it can be confirmed that the participants generally applied the spin in the correct direction for both back spin (cue ball travelled back) and top spin (cue ball continued to move forward). This is further supported by the lower cue tip height in the back spin shots compared with the top spin shots. Learning from coaches and elite players, players should not elevate the cue stick butt when delivering the cue stick, in order to try to keep the cue stick parallel to the playing surface of the pool table. While the cue stick angle in the back spin test was significantly greater than in the top spin test, it was approximately within the range of 4^{o} to 6^{o} for all participants. This observation confirmed that the cue stick butt was not much elevated regardless of the type of spin applied to the cue ball. According to the feedbacks provided by the participants during the experiment sessions, the back spin test was more difficult than the top spin test. Participants' subjective perceived challenge corresponded well with the higher cue tip speed required in the back spin test than the top spin test. While the cue tip speed in the current study (around 1 m/s for the top spin test and 3 m/s for the back spin test) were both lower than those reported in the earlier snooker study (roughly 2.5 m/s for top spin test and 4 m/s for the back spin test) (Kong et al., 2021), it should be acknowledged that the snooker table are bigger (356.9 cm × 177.8 cm) than the 9-ball table and the shot distances were longer than the settings in this study, and hence, greater cue tip speeds and stronger spins were needed in snooker than the results of this present study. The greater joint ROM and maximum angular velocities in the back spin test were likely to contribute to the higher cue tip speed at impact than the top spin test. The higher cue tip speed for the back spin shots could be a requirement for sufficient back spins to draw the cue ball backward upon impacting the object ball. Collectively, coaches and players should note the different techniques in the cue-wielding arm to effectively deliver the cue stick when executing back spin and top spin shots.

There were a few limitations to the current study. Firstly, this study only investigated the forward swing and follow-through phases of the cueing movement because these phases directly contributed to the cue stick delivery. Future studies may consider including other phases, such as the aiming phase and practice swings, which may relate to stance stability and aiming accuracy. Secondly, all participants had at least one-year playing experience in the present study, and this may have contributed to the lack of between-group differences. Complete beginners were not included in this study because they may not be able to perform the required back spin and top spin shots. It will be of interest to explore the learning progress of beginners over time to see when the kinematics of the cueing movement start to stabilise. Thirdly, the participant allocation using the 15-ball test may be over-simplistic. While the 15-ball test was effective in examining players' overall skill levels and associated with specific skills (Pan, Komar, & Kong, 2021), no significant differences in top spin or back spin shot performance (error distance) were observed in this study across the novice, intermediate, and skilled players grouped according to their 15-ball test results. The grouping method could also contribute to the lack of between-group differences in upper body kinematics. Hence, it is worth considering utilising other approaches, such as cluster analysis, to rank or group participants. Lastly, this study only investigated the kinematic variables of joints in isolation. In the future, studies are warranted to assess the inter-joint coordination when delivering the cue stick. Other aspects, such as muscle activation and joint kinetics could also be studied to better understand the cueing movement.

Conclusion

In the back spin and top spin shots, no significant differences in shot performance were found among the novice, intermediate, and skilled groups. When performing cue sports shots, the kinematics of cue-wielding arm, trunk, and cue stick were not significantly different among players of different skill levels. Compared with the top spin shots, greater joint range of motion and angular velocities were required in the back spin shots to effectively deliver the cue stick at a higher speed at impact. Greater magnitude of head movements in the anteroposterior direction was observed in the novice players compared with the skilled players, suggesting that novice players exhibit non-relevant head movements which may impair stance stability. Future studies could consider investigating other aspects of the cueing movement such as inter-joint coordination and muscle activation.

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References

Arutyunyan, G. A., Gurfinkel, V. S., & Mirskii, M. L. (1968). Investigation of aiming at a target. *Biophysics*, *13*(3), 642–645.

Arutyunyan, G. A., Gurfinkel, V. S., & Mirskii, M. L. (1969). Organization of movements on execution by man of an exact postural task. *Biophysics*, *14*(6), 1162–1167.

Chung, D. H. S., Griffiths, I. W., Legg, P. A., Parry, M. L., Morris, A., Chen, M., Griffiths, W., &

Thomas, A. (2014). Systematic snooker skills test to analyze player performance. *International Journal of Sports Science & Coaching*, *9*(5), 1083–1105. https://doi.org/10.1260/1747-9541.9.5.1083

Dounskaia, N. (2005). The internal model and the leading joint hypothesis: implications for control of multi-joint movements. *Experimental Brain Research*, *166*(1), 1–16. https://doi.org/10.1007/s00221-005-2339-1

Gates, D. H., Walters, L. S., Cowley, J., Wilken, J. M., & Resnik, L. (2016). Range of motion requirements for upper-limb activities of daily living. *The American Journal of Occupational Therapy*, *70*(1), 7001350010p1-7001350010p10. https://doi.org/10.5014/ajot.2016.015487

Haar, S., Sundar, G., & Faisal, A. A. (2021). Embodied virtual reality for the study of real-world motor learning. *PLOS ONE*, *16*(1), e0245717. https://doi.org/10.1371/journal.pone.0245717

Haar, S., van Assel, C. M., & Faisal, A. A. (2020). Motor learning in real-world pool billiards. *Scientific Reports*, *10*(1), 20046. https://doi.org/10.1038/s41598-020-76805-9

Jankunas, J., & Zare, R. N. (2014). Why some pool shots are more difficult than others. *Resonance*, *19*(2), 116–122. https://doi.org/10.1007/s12045-014-0015-0

Kantz, H., & Schreiber, T. (2004). *Nonlinear time series analysis* (2nd ed.). Cambridge University Press. https://books.google.com.sg/books?id=RfQjAG2pKMUC

Kong, P. W., Pan, J. W., Chu, D. P. K., Cheung, P. M., & Lau, P. W. C. (2021). Acquiring expertise in precision sport – what can we learn from an elite snooker player? *Physical Activity and Health*, *5*(1), 98–106. https://doi.org/10.5334/paah.111

Kornfeind, P., Baca, A., Boindl, T., Kettlgruber, A., & Gollnhuber, G. (2015). Movement variability of professional pool billiards players on selected tasks. *Procedia Engineering*, *112*, 540–545. https://doi.org/10.1016/j.proeng.2015.07.240

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Frontiers in Psychology*, *4*(NOV), 1–12. https://doi.org/10.3389/fpsyg.2013.00863

Latash, M. L., Scholz, J. P., & Schöner, G. (2002). Motor Control Strategies Revealed in the Structure of Motor Variability. *Exercise and Sport Sciences Reviews*, *30*(1). https://journals.lww.com/acsm-essr/Fulltext/2002/01000/Motor_Control_Strategies_Revealed_in_the_Structure.6.aspx

Leider, N. (2010). *Pool and billiards for dummies*. Wiley Publishing. https://books.google.com.sg/books?id=C-mt6DVhbHkC&dq=Leider,+N.+Pool+%26+Billiards+for+Dummies+(Wiley,&source=gbs_navlinks_s

Müller, H., & Sternad, D. (2009). Motor learning: changes in the structure of variability in a redundant task. In *Advances in Experimental Medicine and Biology* (Vol. 629, Issue 585, pp. 439–456). https://doi.org/10.1007/978-0-387-77064-2_23

Pan, J. W., Komar, J., & Kong, P. W. (2021). Development of new 9-ball test protocols for assessing expertise in cue sports. *BMC Sports Science, Medicine and Rehabilitation*, *13*(1), 9. https://doi.org/10.1186/s13102-021-00237-9

Pan, J. W., Komar, J., Sng, S. B. K., & Kong, P. W. (2021). Can a good break shot determine the game outcome in 9-ball? *Frontiers in Psychology*, *12*. https://doi.org/10.3389/fpsyg.2021.691043

Pejcic, B., & Meyer, R. (1993). *Pocket billiards: fundamentals of technique & play*. Sterling

Publishing Co., Inc.

Serrien, B., Witterzeel, E., & Baeyens, J.-P. (2018). The uncontrolled manifold concept reveals that the structure of postural control in recurve archery shooting is related to accuracy. *Journal of Functional Morphology and Kinesiology*, *3*(3), 48. https://doi.org/10.3390/jfmk3030048

White, C. (2017). A comparative study of two types of ball-on-ball collision. *Physics Education*, *52*(4), 045013. https://doi.org/10.1088/1361-6552/aa6d2a

Winter, D. A. (2009). *Biomechanics and motor control of human movement* (4th ed.). John Wiley & Sons, Inc. https://doi.org/10.1002/9780470549148

Wu, G., van der Helm, F. C. T., (DirkJan) Veeger, H. E. J., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A. R., McQuade, K., Wang, X., Werner, F. W., & Buchholz, B. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. *Journal of Biomechanics*, *38*(5), 981–992. https://doi.org/10.1016/j.jbiomech.2004.05.042