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Effectiveness and Kinematic Analysis of Initial Step Patterns for Multidirectional Acceleration in Team and Racquet Sports

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The ability for quick multidirectional accelerations is crucial for athletic performance in team and racquet sports. So far, there has been little research dedicated to different initial step patterns usually applied by players. Therefore, the present study investigated the kinematic characteristics and effectiveness of the following step patterns: Jab Step (JS), Pivot Step (PS), Gravity Step (GS) and Counter Step (CS). Twenty-two male competitive team and racquet sport athletes completed maximum lateral accelerations utilizing the step patterns. Following familiarization with each step pattern, three 5 m sprints (5 m STs) into both directions (left & right) were completed. Sprint times, the translation of the center of mass (CoM) and joint angles were obtained using three-dimensional motion analysis. 5 m STs of the CS were faster compared to the GS and PS for both directions. A detailed distance-time analysis revealed that for shorter distances only the JS was faster than the GS. Regarding the sequence in which the maximum angular velocities (max. $\vec{\omega}$) in the hip, the knee, and the ankle were reached during the push off, there was a proximal-to-distal sequence for the JS and the CS, but a distal-to proximal sequence for the GS and the PS. The results reveal that the JS and the CS are superior for accelerations towards the lateral direction. Specifically, they indicate that the JS is more suitable for covering very short distances and the CS is superior for covering further distances. In addition, the distal-to-proximal sequence of max. $\vec{\omega}$ during the push-off in the GS and the PS might indicate lower kinematic efficiency.

Key words: *change of direction, first step quickness, motion analysis.*

Introduction

During the last decades, technical innovations, rule changes and a greater focus on the physical development of athletes, have led team and racquet sports to become progressively faster. Tennis, for instant, has changed from a predominantly technique-based sport to a highly explosive one that places high demands on the players' ability to accelerate (Fett et al., 2020). In soccer, match analysis from the German Bundesliga showed that sprints were the most frequent actions in situations that resulted in a goal (Faude et al., 2012). In line with this, analyses from the English Premier League showed that rapid accelerations combined with quick changes of direction were the most frequent actions that led to a goal (Martínez-Hernández et al., 2022). In the highest Spanish basketball league (ACB), rule changes made the game more dynamic and faster, which is clearly reflected in the anthropometric and the athletic profile of players (Alejandro et al., 2015). More general, athletes of different playing levels often differ in the speed they can achieve (Cometti et al., 2001). This highlights the steadily increasing importance of running speed in team and racquet sports.

However, in team and racquet sports, it is rather about covering short distances as fast as possible than reaching and maintaining top speed. Therefore, it is the ability to accelerate one's body as quickly as possible that can be decisive for game-changing situations (Cronin and Hansen, 2005; Murphy et al., 2003; Northeast et al., 2019; Taylor et al., 2017). For instance, it may be a matter of leaving an opponent behind, to position oneself well in advance or to confront an attacking

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opponent. Assumed by practitioners and confirmed by studies, performance at short accelerations (e.g., 5 m) and maximum sprint speed (e.g., > 30 m) are considered distinct and specific qualities (Delecluse et al., 1995; Young et al., 2001).

In this context, especially athletes in team and racquet sports need the ability to accelerate quickly in multiple directions. For some, this means accelerations in the sagittal plane (e.g., running straight, running backwards, turning and running), while others require more lateral movements (e.g., defensive movements, baseline movements in racquet sports) (Taylor et al., 2017; Vuong et al., 2022). The resulting requirements are multidimensional. Athletes must be able to perceive and evaluate the situation cognitively, adjust their body position, optimally activate the needed muscles, and develop force in the right direction.

Since acceleration performances strongly depend on the first steps (Frost and Cronin, 2011), it is of high practical interest to examine these in detail. It is well established that the angular displacement of the body's center of mass (CoM) in relation to the vertical axis through the point of support determines the propulsive force development (Kugler and Janshen, 2010). From a movement technical perspective, various possibilities are conceivable to get into such a body position as quickly as possible. Regarding this, certain step patterns may have a beneficial effect on the subsequent sprint time (Bragg and Andriacchi, 2001; Filipcic et al., 2017; Frost and Cronin, 2011). To the best of our knowledge, only few studies exist on different movement strategies (step patterns) regarding the first few steps in accelerations. The following step patterns can be derived from these studies: the Jab Step (*Forward-moving Sidestep*) (JS), the Pivot Step (*Pivoting Crossover*) (PS), the Gravity Step (GS) and the Counter Step (*False Step*) (CS) (Bragg and Andriacchi, 2001; Frost and Cronin, 2011; Hewit et al., 2010; Kraan, 2001).

Therefore, the present study aims to investigate the effectiveness and the kinematic characteristics of the initial step patterns for multidirectional accelerations in team and racquet sports. In order to achieve this aim, the first objective of the study was to identify which step patterns were intuitively used in multidirectional accelerations by team and racket sport athletes, whereas the second objective was to identify which of the four techniques were more effective for linear acceleration from a lateral direction (90° to the starting position). For this purpose, high level athletes (3rd division soccer, 2nd division volleyball, 2nd division basketball) were asked to complete acceleration tasks in six different directions related always to the same starting position. The intuitive step patterns used in multidirectional accelerations were categorized according to the literature as the JS, PS, GS and CS (Bragg and Andriacchi, 2001; Frost and Cronin, 2011). These step patterns were then investigated for accelerations within the lateral direction with regard to their effectiveness (5 m ST) as well as their kinematic characteristics.

Methods

Participants

Twenty-two male high level (3rd division soccer, 2nd division volleyball, 2nd division basketball) team- and racquet sport athletes (age: 22.1 ± 2.7 years; body height: 185.9 ± 7.3 cm; body mass: 84.1 ± 9.9 kg) volunteered to participate in this study (inclusion criteria: male, 18–30 years of age, at least three years of high-level competitive team or racquet sport experience). Exclusion criteria were acute illnesses or injuries that did not allow or would impair exercises at maximal intensity. Participants were requested to avoid any intensive training within 48 hours prior to the examination. Before the study started, all participants were informed in detail about possible risks and data privacy policy. Each participant could cancel their participation at any time without providing a reason. Written informed consent was obtained from the participants. The study design, procedures and measurements were approved by the Ethics Committee of the Faculty of Sports Science of the Ruhr University Bochum (EKS V 25/2020) and in line with the Declaration of Helsinki.

Measures

Anthropometrics

The InBody 770 scale (Gangnam-gu, Seol, South Korea; measurement accuracy ± 0.1 kg) and a stadiometer (Holtain Ldt., Crosswell, UK; measurement accuracy ± 0.01 m) were used to assess body mass and body height of participants. Furthermore, a precision caliper (Toom GmbH, Cologne, Germany, measurement accuracy ± 0.01 m) was used to measure additional anthropometric data (leg length, knee width, ankle width, sole thickness, elbow width, wrist width, shoulder offset, hand thickness) required for three-dimensional analyses.

Five-Meter Sprint Time (5 m ST)

Sprint times were recorded over a distance of 5 m using a photoelectronic double light gate system (Witty System, Microgate, Bolzano, Italy; measurement accuracy ± 0.001 s). The distance between the light gates and the respective reflectors was 2 m. The time measurement was initiated by a starting signal, which was positioned in front of the athlete.

Motion Analysis

For the first part of the study (recording of step patterns during multidirectional accelerations), a Sony Handycam FDR-AX53 (Sony, Tokyo, Japan; measurement accuracy: 50 fps) was used, which was positioned behind athletes in such a way that the first two steps could be recorded in slowmotion. Based on the video material, the intuitively chosen step patterns were categorized into the four step patterns derived from the literature. For the second part of the study, an iPhone XR (Apple Inc., USA, Cupertino; measurement accuracy: 240 fps) was used to measure the reaction time via video analysis as well as to check whether the required step pattern had been used correctly. The reaction time to the external stimulus was extracted by means of video analysis for all runs as the time difference between the appearance of the starting signal and the initiation of movement.

Three-dimensional motion recordings of all trials of the four step patterns (JS, PS, GS, CS) were captured using the ©Vicon Motion Capture System (Ltd., Oxford, UK; measurement accuracy: 400 Hz), which consisted of eight Vantage V5 cameras. Three-dimensional analysis of the recorded step patterns was conducted using Conventional Gait Model 2 (CGM2) (Leboeuf et al., 2019). The following variables were calculated from the kinematic data: a) time required by the CoM from movement initiation to reaching defined distances (t 25, 50, 100 cm) b) hip, knee and ankle joint kinematics: changes in joint angles over the first step were measured to calculate the corresponding max. $\vec{\omega}$ at the moment of the push off (Figure 1). An overview of the variables can be found in Table 1.

Data Processing

Data processing and analysis were carried out using Vicon Nexus 2.11 (©Vicon Motion Capture System Ltd., Ocford, UK) and Microsoft Excel (version 16.16.5; Microsoft Corp., Redmond, USA). Vicon Nexus was used to define and calculate segments and joint centers. The kinematic variables were calculated via the changes of the segments in relation to each other. Additionally, max. $\vec{\omega}$ during the push off was determined using Vicon Nexus. The obtained data were exported as CSV. files and imported into Microsoft Excel. In Microsoft Excel the data were converted from frames per second to seconds. Data of all participants were then averaged and cut to the length of the shortest available trial. Moreover, curve smoothing using a moving average over 30 frames was calculated for the illustration of the CoM course.

Design and Procedures

Testing was conducted in two sessions, separated by one week. Part A consisted of testing and recording the intuitive step patterns when accelerating in six different directions (Figure 3A). In addition, familiarization with the step patterns was carried out on this day. In part B, each of the four step patterns (JS, PS, GS & CS) was tested for maximum accelerations to the lateral (90° to the starting position) and recorded using motion capturing technology (©Vicon Motion Capture System Ltd., Ocford, UK) (Figure 3B). The step patterns are illustrated in Figure 2. All sessions took place in a 20 x 10 m indoor laboratory on a non-slipping floor (Rebound Ace©). The room temperature was kept constant at 20 degrees for all sessions. A standardized ten-minute warm up was performed before each session, consisting of dynamic stretching and sprint-preparation (e.g., running ABC´s) exercises. For all multidirectional accelerations, a recovery time of 30 s between trials and a 3-min recovery after three trials were maintained.

Familarization

To familiarize participants with the different step patterns for lateral accelerations (90° to the starting position), the step patterns were practiced on the first testing day. Therefore, the step patterns were performed with maximum intensity until the participants' 5 m ST for three trials fell within a deviation of 2.5%, based on the fastest trial. If a participant needed so many trials that fatigue effects overlapped sprint performances in such a way that the defined performances could not be achieved, a second familiarization session was carried out.

Testing Sessions

Part A: The intuitively chosen step patterns for accelerations over a distance of 5 m in six different directions relative to the starting position were captured. For this purpose, participants executed three maximum attempts in each of the directions. The running direction was always known in advance and the start occurred as a reaction to an optical signal that was positioned in front of them. All sprints were initiated from a stationary athletic ready position. This was achieved by lowering the body's center of mass while keeping the upper body upright. The exact setup of this test section is shown in Figure 3A.

Part B: To measure the 5 m ST and the kinematic variables of the four trained step patterns, participants completed maximum sprints in a lateral direction (90° to the starting position to the left or right) over a distance of 5 m. For each step pattern, three trials were performed in both lateral directions (left and right). The sequence of the four step patterns was counterbalanced, matching the number of participants who performed each step pattern as the first, second, third, and fourth tasks, respectively. The knowledge of the running direction, the starting signal and the starting position were identical to those in part A. Participants were instructed to accelerate as quickly as possible out of the athletic ready position using the predefined step pattern in the corresponding direction as soon as the starting signal appeared. To minimize fatigue effects a rest interval of 30 s was kept between each attempt and after three attempts a 3 min recovery period was given. The exact setup of this test section is shown in Figure 3B.

Statistical Analysis

The different step patterns were categorized by video analysis and statistically evaluated with regard to their distribution depending on the running direction, using the chi square test. Furthermore, the results of the four step patterns were given by the arithmetic mean as a measure of the central tendency and the corresponding standard deviation (SD) as a measure of dispersion. Data were checked for normal distribution using the Shapiro-Wilk test. In the event of normality, differences between step patterns were calculated using a multifactorial ANOVA with repeated measures. For the calculation, the two factors "step pattern" and "direction" were defined. The step pattern factor consisted of four levels and the direction factor of two levels. The underlying significance level was $p \leq 0.05$. The α-level was adjusted using Tukey's correction. Statistical analysis was performed using SPSS analysis software (version 27.0; SPSS Inc., Chicago, USA) and Microsoft Excel (version 16.16.5; Microsoft Corp., Redmond, USA).

Results

The comparison of the step patterns in respect to the running directions by means of the chi square test showed significant differences (X^2 (432, 21) = 80.1, $p < 0.001$). As illustrated in Figure 4, the percentage distribution shows that the CS was applied most frequently for all directions. However, the other step patterns were used comparatively more frequently for the lateral running directions. In terms of frequency, most often the CS, second the JS, third the PS and least often the GS was used.

Comparisons of the step patterns using multifactorial analysis of variance with repeated measures indicated differences between the step patterns in the 5 m ST (F (3,352) = 19.165, $p < 0.001$) as well as for t 50 and 100 cm (F (3,86) = 10.2767, $p < 0.001$). However, no difference was found with regard to the running direction as well as for t 25 cm.

Post hoc pairwise comparisons revealed that the 5 m ST for the GS was slower than for the JS and the CS. Moreover, it turned out that the PS was slower than the CS (range of mean difference: -0.102–0.057 s; smallest lower 95% CL: 0.25 s, highest upper 95% CL: 1.41 s; p_{Tukey}: 0.001–0.049).

For t 50 and 100 cm, pairwise comparisons showed that the GS was slower than the JS (range of mean difference: 0.093–0.105 s; smallest lower 95% CL: 0.545s, highest upper 95% CL: 2.52 s; p_{Tukey}: < 0.005–0.025). The mean course of the CoM for the step patterns and the running directions is shown in Figure 5.

The comparison by means of analysis of variance with repeated measures of the timing order regarding max. $\vec{\omega}$ of the hip, knee and ankle joints of the leg that realized the push off of the first step revealed differences in those sequences (F (3,42) = 10.7, $p < 0.001$). For the JS and the CS, the push off of the first step was realized by the contralateral leg, while for the PS and the GS, it was the ipsilateral leg. Post hoc pairwise comparisons revealed differences for the time intervals of the JS and the CS to the GS in both directions (range of mean difference: -0.03–0.02 s; smallest lower 95% CL: -0.02 s, highest upper 95% CL: 0.02 s; p_{Tukey}: < 0.001–0.004). The average sequential differences and their standard deviations are illustrated in Figure 6.

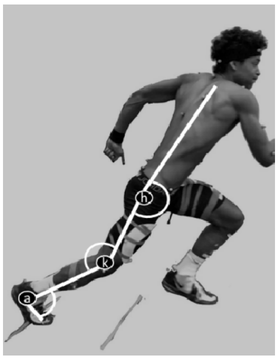

Figure 1. *Changes in hip (h) knee (k) and ankle (a) joint angles in the sagittal plane were measured for the leg that realized the first acceleration.*

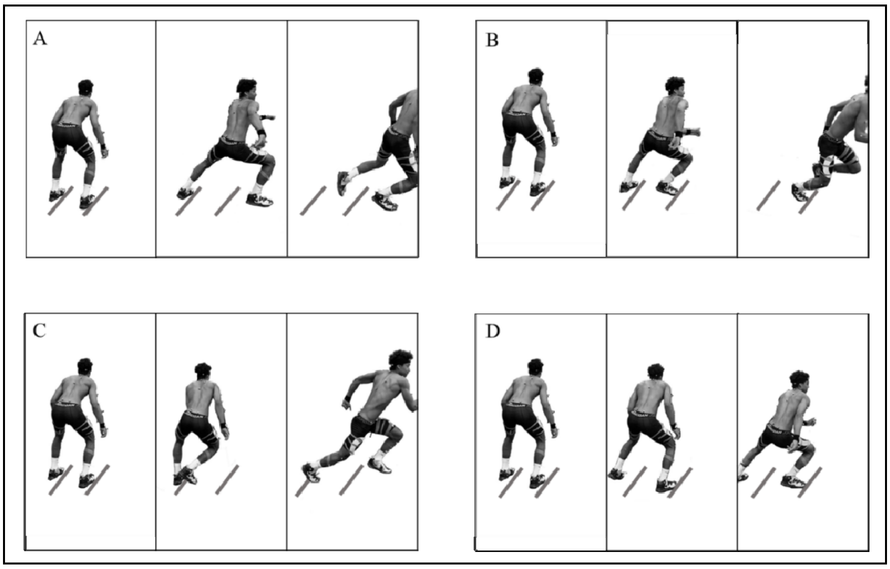

Figure 2. *Illustration of the four step patterns. A) shows the Jab Step (JS), B) shows the Pivot Step (PS), C) shows the Gravity Step (GS) and D) shows the Counter Step (CS).*

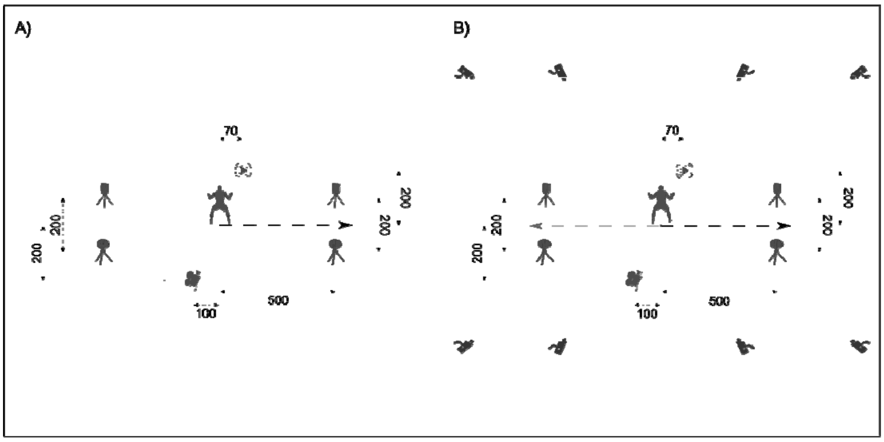

Figure 3. *A) Test setup for recording the step patterns used intuitively during accelerations in eight different directions; B) Test setup for recording four specified step patterns for accelerations to the lateral (90° to the starting position); other running directions = running directions measured in the course of the investigation, actual running direction = the running direction measured in the actual attempt.*

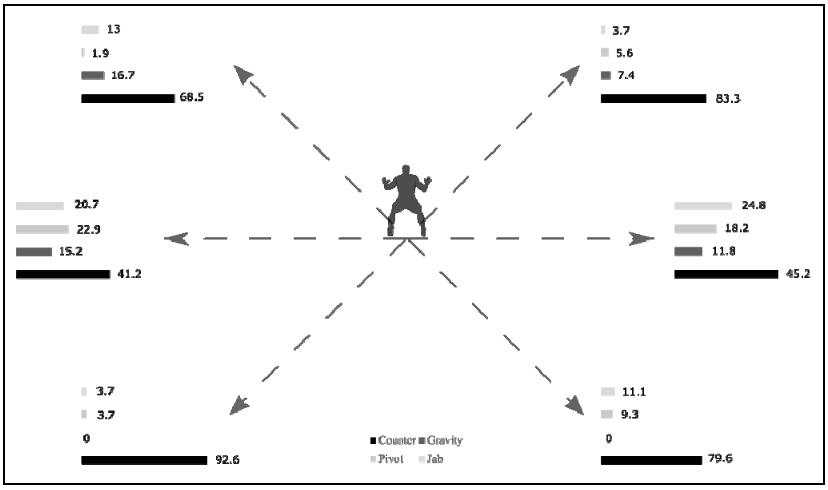

Figure 1. *Distribution of intuitively chosen step patterns (shown as percentages) illustrated for each of the eight directions (running directions: 0°, 45°, 90°, 135°, 180°, 225° clockwise relative to the starting position). (X^2 (432, 21) = 80.1, p < 0.001).*

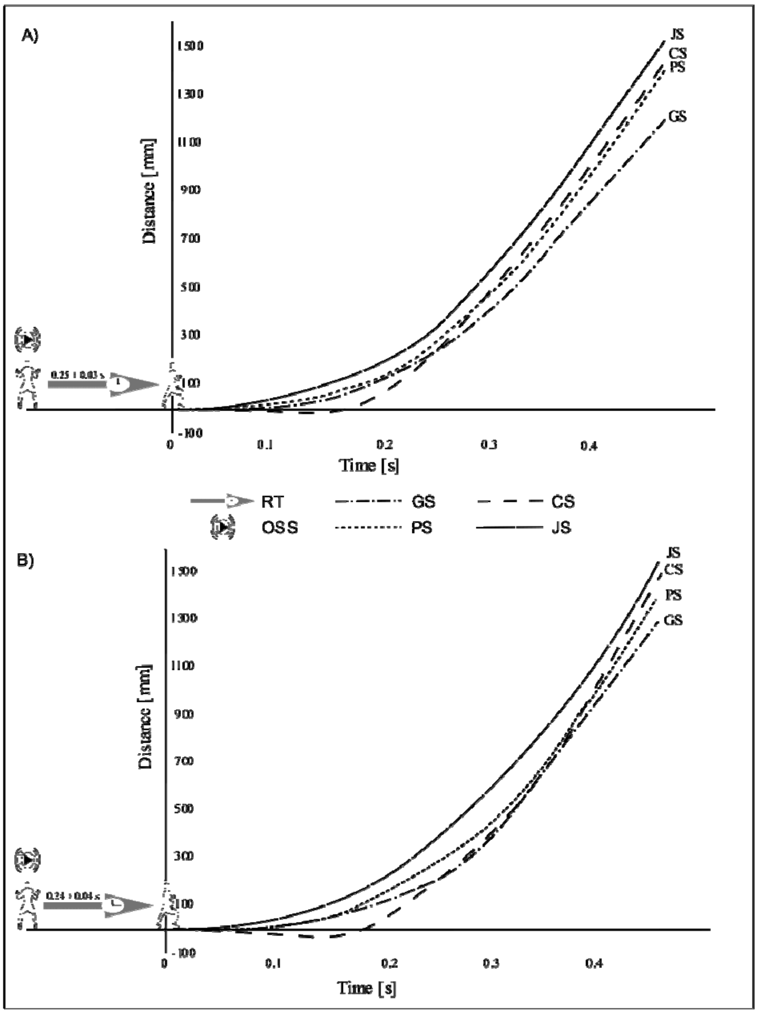

Figure 2. *A) Average course of the CoM in the sagittal plane of the various step patterns for the running direction to the left; B) average course of the CoM in the sagittal plane of the various step patterns for the running direction to the right. GS = Gravity Step; CS = Counter Step; PS = Pivot Step; JS = Jab Step; RT = reaction time (0.244 ± 0.042 s to the right; 0.255 ± 0.033 s to the left); OSS = optical starting signal.*

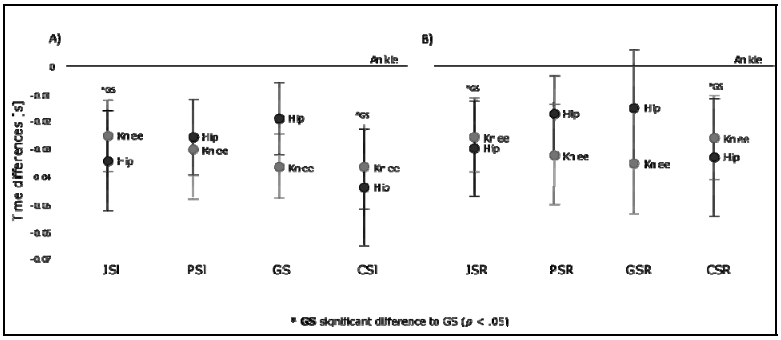

Figure 3. *A) Timing differences of max. $\vec{\omega}$ achieved in the hip, knee and ankle joints of the leg that realized the first push off for the attempts to the left; B) timing differences of max. $\vec{\omega}$ achieved in the hip, knee and ankle joints of the leg that realized the first push off for the attempts to the right. Since the ankle reached max. $\vec{\omega}$ last in all cases, this was set to zero so that the other variables are shown relative to the ankle (n = 22).*

Table 1. *Overview of the dependent variables.*

Name	Definition
t 25 cm t 50 cm t 100 cm	Time from movement initiation until the CoM reached defined distances of 25, 50 and 100 cm in the sagittal plane; in seconds; reaction time subtracted; for both directions; recorded using the Vicon system
5 m ST	Total time over 5 m; for both directions; in seconds; reaction time subtracted; recorded using photoelectric double light gates
Max. $\vec{\omega}$ in the hip Max. $\vec{\omega}$ in the knee Max. $\vec{\omega}$ in the ankle	Maximum angular velocities achieved in the hip, knee and ankle joints around the transversal axis of the leg that realized the first push off (in targeting direction for the GS and the PS, contralateral for the CS and the JS); recorded using the Vicon system; for both directions

Table 2. *Mean ± SD for t 25, 50, 100 cm and 5 m ST (n = 22).*

		t 25 cm [s]		t 50 cm [s]			t 100 cm [s]			5 m ST [s]		
		Mean	SD	Mean	SD		Mean	SD		Mean	SD	
CS	L	0.20	± 0.06	0.28	± 0.05		0.43	± 0.08		1.21	± 0.09	** / ***
	R	0.20	± 0.06	0.31	± 0.05		0.44	± 0.04		1.21	± 0.05	
GS	L	0.20	± 0.05	0.34	± 0.07	*	0.50	± 0.05	*	1.29	± 0.06	
	R	0.19	± 0.08	0.34	± 0.07		0.50	± 0.07		1.31	± 0.08	
JS	L	0.14	± 0.03	0.25	± 0.06		0.40	± 0.06		1.24	± 0.08	**
	R	0.14	± 0.05	0.27	± 0.08		0.40	± 0.07		1.25	± 0.09	
PS	L	0.18	± 0.05	0.28	± 0.05		0.45	± 0.05		1.27	± 0.09	
	R	0.17	± 0.10	0.27	± 0.08		0.43	± 0.08		1.26	± 0.09	

* = significant difference to JS; ** = significant difference to GS; *** = significant difference to PS

Discussion

To the best of our knowledge, this study is the first that provides differentiated information on the effectiveness and kinematic characteristics of different initial step patterns that are commonly used for accelerations to the lateral direction. More specifically, the purpose of the present work was to investigate whether the selected initial step patterns differed regarding the resulting sprint performances over different distances. Furthermore, the aim was to investigate whether the step patterns varied with regard to the sequence of max. $\vec{\omega}$ achieved by the hip, the knee and the ankle during the push off. Our results indicate that for multidirectional accelerations over distances of 5 m, the CS was chosen most frequently. Moreover, the JS tended to be superior over short distances (i.e., 50–100 cm), but was exceeded by the CS when the distance increased. The kinematic analysis revealed that the two faster variants (JS & CS) showed expected proximal-to-distal sequencing in terms of achieving max. $\vec{\omega}$ of the hip, knee and ankle joints during the initial push off, while the other two variants (PS & GS) reached max. $\vec{\omega}$ of the hip before the knee.

A conceivable reason for the superiority of the JS over the short distances (i.e., 50–100 cm) lies in the expansive first step of the ipsilateral leg. This enables an immediate translational acceleration of the CoM in the desired direction with simultaneously more time relative to the CS for concentric force production in the push off leg due to a longer ground contact time (Kawamori et al., 2013; Miyanishi et al., 2017; Nummela et al., 2007). In addition, the same step enables the breaking of the dynamic balance through the ipsilateral leg knee lift and thus, overcoming the body's own inertia, which at least in the PS must be initially achieved by the push off. Various studies have shown that overcoming inertia by leaning the body in the desired direction is an important part of acceleration performance (Bezodis et al., 2015; Havens and Sigward, 2015; Hewit, 2010; Kraan, 2001; Kugler and Janshen, 2010).

Accordingly, a possible rationale for the advantage of the CS for acceleration over longer distances (i.e., 5 m) is due to the breaking of the body´s dynamic balance, so that the horizontal force production is supported by the resulting leaned-forward body position. The initial movement towards the opposite direction favors the leaning of the body towards the running direction. Additionally, the initial countermovement enables an effective use of the stretch-shortening cycle, which results in an enhanced push off impulse. This is in line with the findings of other studies that showed that an initial step in the counter direction resulted in a quicker peak of force during the push off (Frost and Cronin, 2011; Kraan, 2001). Consistent with that, most of the test persons intuitively decided to use the CS. Meanwhile, the same countermovement is causing the CS to be slower than the JS over shorter distances. While acceleration in the desired direction can be initiated immediately with the JS, with the CS the CoM initially moves in the opposite direction. In the course of the CoM, it becomes obvious that the CS is initially the slowest, but later overtakes the other step patterns (Figure 5).

Interestingly, the initial countermovement of the GS did not lead to a good sprint performance. In fact, this step pattern was clearly the slowest. This is potentially due to a pronounced rotational component caused by the ipsilateral leg moving back and the contralateral leg moving forward towards the lateral running direction relative to the starting position. Therefore, this might be different when the running direction is changed in relation to the starting position. More precisely, it is conceivable that the acceleration performance using this step pattern would be better if the running direction was laterally forward. Appropriately, another study with tennis players identified this step pattern as the quickest for diagonal forward accelerations aiming to return a tennis ball (Bragg and Andriacchi, 2001).

Regarding kinematic characteristics, a number of studies have shown that a proximal-to-distal sequence in terms of reaching max. $\vec{\omega}$ of the hip, the knee, and the ankle during the push off is required for optimal acceleration performance (Chiu et al., 2014; Ibrahim et al., 2020; Lockie et al., 2012). The kinematic analysis of the push off for the different step patterns showed that this order was only achieved with the two faster patterns (JS & CS). With the PS and the GS, max. $\vec{\omega}$ in the hip was reached after that in the knee. Assuming that proximal-to-distal sequencing of max. $\vec{\omega}$ during the push off is necessary for optimal acceleration, these results provide an explanation for the poorer performance of these step patterns.

A central limitation of the study is that the CS is obviously the most intuitive step pattern (Figure 4), therefore, it is conceivable that this step pattern was coordinatively best mastered. Thus, it is not clear whether the suboptimal sequencing of the GS and the PS is a kinematic characteristic or due to technical deficiencies. Further research is needed to investigate this in more detail. Another limitation could be the lower limb laterality of participants, which was not considered in the present study. However, this is difficult to determine precisely, especially since the limb preference can differ between movement tasks involving the manipulation of objects (e.g., balls) and stabilization or force-generating (jumping) tasks. One possibility for upcoming studies to find out laterality of the lower limbs could be the recording of unilateral force data.

Practical Implications

Basically, the results of the present study reveal that the JS and the CS are more effective in terms of sprint performance in lateral accelerations than the PS and the GS.

Furthermore, the step pattern dependent acceleration performances over various distances suggest that the choice of the optimal initial step pattern depends on the practical context, meaning that distance matters, which is determined by the situation-specific requirements. In particular, when it comes to making small adjustments to one's position, the JS seems to be the best step pattern. This occurs, for instance, when drawing an offensive foul in basketball, adjusting one's position to the ball in tennis before executing a groundstroke, or moving defensively with short steps to keep an attacker in front of oneself. However, when it comes to breaking away from a defender or running for a difficult ball, the CS is the most efficient step pattern. Therefore, using the CS might be an advantage for offensive players, as the opponent is forced to react and thus, one step behind. On the one hand, this sets the precondition for optimal acceleration, on the other hand, the contralateral first step can be used as a form of body feint. Accordingly, the context of the movement is crucial for training footwork and initial step patterns. For those situations that require traveling very short distances, the JS should be practiced, while the CS should be practiced for covering longer distances. Although the results of the present study show that the PS and the GS are slower and suboptimal in terms of proximal-to-distal sequencing, these step patterns could also be advantageous in certain situations (e.g., confusing an opponent by accelerating through the ipsilateral leg). The present results provide practical recommendations for training and competition in team and racquet sports, as well as further research potential.

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