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INTRA-LIMB KINEMATIC STRATEGIES OF MAXIMUM VELOCITY PHASE SPRINT RUNNING PERFORMANCES

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This study aimed to develop insight into the intra-limb kinematic strategies underpinning athlete- and step-based sprint running performances. Joint centre coordinate data were automatically tracked for maximum velocity phase sprint running trials of six well-trained athletes. The fastest athlete initiated the stance phase with a 16.0º and 3.4º more extended ankle and knee, and a corresponding 5.8º more flexed hip joint compared to the slowest athlete (*$p<0.05$*). In contrast, the fastest and slowest steps were typically executed using similar intra-limb kinematics in the stance and recovery phase. More successful athletes may be distinguished by the intra-limb kinematic strategy employed while the robustness of the step-based measures suggested the use of a common, localised strategy regardless of diverse performances.

KEY WORDS: step characteristics; stance; recovery; lower limb.

INTRODUCTION: Successful sprint running is determined by the horizontal displacement covered in each step (step length) and the number of steps produced over a given time (step frequency). Although the level and nature of a sprinter's effort may be determined by examining step characteristics alone, consideration of the underlying movement patterns (kinematic strategies) has been considered necessary to gain insight into how a performance is physically produced (Mann & Herman, 1985).

Traditional research has suggested that the action of the leg during stance contributes to an improved step length and frequency, and may be a major determining factor of sprint running performance (Mann & Sprague, 1980). Several hypotheses regarding the intra-limb strategies underpinning sprint running performance have since been proposed. The angle of the thigh in stance and the shank at touchdown were considered critical determinants of elite athlete performance differences (Mann and Herman, 1985). The hip-extensor theory, which was recently described by Hunter et al. (2004) attributed increased horizontal velocity to the large propulsive forces incurred in stance by the hip extensor action. The achievement of faster maximum speeds by the production of large ground reaction forces was similarly advocated by Weyand et al. (2000) but a more rapid repositioning of the lower limb was not considered a primary determinant. More recently, Gittoes and Wilson (2010) highlighted the key mechanical role of the coupled knee and ankle joint actions during the step phase of maximum velocity phase sprint running.

With a typical popularity of interest in stance phase mechanics, the free limb's role in step velocity development has remained less well understood. The generation of greater maximum thigh and shank angular speeds in recovery (early swing) phase were proposed as key indicators of superior sprint performances by Mann (1985). The important role of the swing phase knee and hip flexion actions in the development of longer steps and faster running velocities was later highlighted by Novacheck (1998). However, Weyand et al. (2000) has since suggested shorter minimum swing times and the rate of limb repositioning in swing were inconsequential in generating faster top running speeds.

The tendency for group analyses in recent years has potentially masked mechanical understanding of sprint running performance. More sensitive, individual analyses have subsequently been advocated by Salo et al. (*in press*) for the examination of sprint running mechanics. Examination of the preferred kinematic strategies used in athlete-specific and individual step performances may consequently extend insight into important mechanical contributors to sprint running performance. The aim of this study was to develop understanding of the phase-related, intra-limb kinematic strategies underpinning individual athlete- and step-based maximum velocity phase sprint running performances.

METHODS: Six well-trained male sprint athletes (mean ±SD age: 20.2 ±0.8 years; mass: 73.5 ±7.5 kg; height: 1.807 ±0.051 m) who competed at university level or above provided written informed consent for the study. The study protocol was ethically approved by the University's Research Ethics Committee and required each athlete to perform four indoor sprint running trials covering a distance of approximately 70 m. Sagittal plane coordinate data of active markers located on the lateral aspect of the left side of the body, and the medial aspect of the right lower limb were obtained for the maximum velocity phase of the running trials using two co-aligned CODA 6.30B-CX1 scanners (sample rate: 200 Hz). The two-dimensional coordinate data were low-pass filtered (cut-off frequency: 15 Hz) and used to determine individual touchdown and toe-off events, and step characteristics. Two independent steps initiated with a left lower limb touchdown were selected from each trial. Time normalised left lower limb joint kinematic profiles were derived for the respective steps. Discrete intra-limb kinematic measures were separately established for stance and recovery (early swing) phases, which are defined in Figure 1.

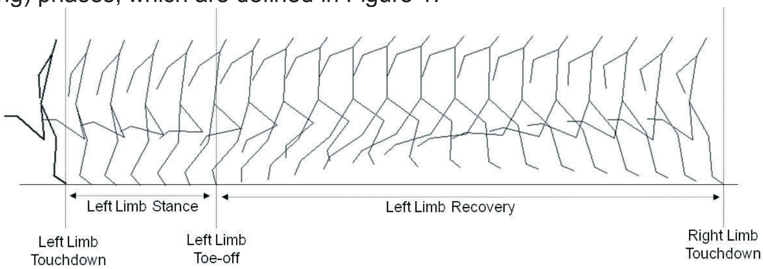

Figure1: Schematic representation of step events (touchdown and toe-off) and phases (stance and recovery) for a maximum velocity phase sprint running trial.

The fastest and slowest athletes were identified by the largest and smallest athlete-specific mean step velocity respectively, which was determined across the eight steps analysed for each athlete. The intra-limb kinematic measures were subsequently compared between the two athletes in order to develop insight into athlete-based strategies underpinning the respective performances. Step-based strategies were examined by comparing the mean kinematic measures of the fastest and slowest steps of all athletes such that six steps (n = one for each athlete) formed the fastest category and six steps (n = one for each athlete) defined the slowest. Athlete- and step-based differences in the intra-limb kinematic strategies of stance and recovery were subsequently examined using an independent and paired t-test (α level of 0.05), respectively.

RESULTS: The individual fastest and slowest athletes were distinguished (*$p<0.05$*) by mean ±SD step velocities (Table 1) of 8.84 ±0.25 $m.s^{-1}$ and 7.87 ±0.13 $m.s^{-1}$ respectively. Marginally smaller step velocity differences (*$p<0.05$*) were produced between the fastest (mean ±SD of 8.93 ±0.65 $m.s^{-1}$) and slowest (mean ±SD of 8.23 ±0.30 $m.s^{-1}$) individual steps while step length and frequency were similar between the respective steps.

Table 1
Intra-limb step characteristics of the fastest and slowest athletes, and fastest and slowest individual steps

	Athlete				Step			
	Fastest		Slowest		Fastest		Slowest	
Step Velocity ($m.s^{-1}$)*#	8.84	±0.25	7.87	±0.13	8.93	±0.65	8.23	±0.30
Step Length (m)*	2.14	±0.04	2.02	±0.03	2.20	±0.12	2.17	±0.17
Step Frequency (Hz)*	4.12	±0.07	3.90	±0.05	4.06	±0.33	3.81	±0.22

Significant difference (*$p<0.05$*) between fastest and slowest: * athletest; # individual steps

The fastest and slowest athletes were correspondingly characterised by diverse ankle, knee and hip kinematics (*p<0.05*) in the stance phase (Table 2). The fastest athlete utilised a 16.0º and 3.4º more extended ankle and knee joint, respectively and a 5.8º more flexed hip joint at touchdown compared to the slowest athlete. Less rapid peak ankle, knee and hip joint extension angular velocities were correspondingly associated with the fastest compared to the slowest athlete. In contrast, the fastest and slowest steps were executed with similar ankle, knee and hip joint configurations and peak angular velocities during the stance phase.

Table 2
Intra-limb kinematic measures of the fastest and slowest athletes and fastest and slowest individual steps for the stance phase

	Athlete				Step			
	Fastest		Slowest		Fastest		Slowest	
Touchdown θA (º)*	130.2	±3.3	114.2	±1.5	121.6	±4.6	114.3	±3.2
Touchdown θK (º)*	155.0	±3.0	151.6	±1.4	166.5	±5.8	151.7	±4.7
Touchdown θH (º)*	146.9	±1.1	152.7	±6.6	153.0	±7.2	149.6	±3.4
Peak Ext θA (º)*	130.2	±3.3	119.4	±3.4	124.4	±3.8	123.6	±2.4
Peak Ext θK (º)*	155.0	±3.0	151.7	±1.5	156.1	±5.7	155.2	±4.3
Peak Ext θH (º)*	162.9	±2.8	181.9	±3.1	173.3	±6.4	172.1	±8.6
Peak Flex θA (º)*	111.1	±2.0	94.7	±1.2	104.8	±6.5	93.9	±5.8
Peak Flex θK (º)*	146.6	±3.4	141.2	±1.2	155.2	±6.9	142.9	±7.3
Peak Flex θH (º)*	146.9	±0.6	148.8	±0.1	148.8	±1.8	148.9	±3.5
Peak Ext ωA (rad.s^{-1})*	11.7	±1.1	13.5	±0.8	13.5	±1.2	14.1	±1.6
Peak Ext ωK (rad.s^{-1})*	3.2	±0.6	5.2	±0.6	2.6	±1.6	4.9	±1.9
Peak Ext ωH (rad.s^{-1})*	7.5	±0.6	10.0	±0.4	8.0	±2.2	9.8	±2.0

θA θK θH = ankle, knee and hip joint configurations, respectively; Ext = extension; Flex = flexion; ωA, ωK, ωH = ankle, knee and hip joint angular velocity, respectively. *Significant difference between fastest and slowest athletes at p<0.05; #Significant difference between fastest and slowest individual steps at p<0.05.

As demonstrated in Table 3, the fastest and slowest athletes utilised diverse ankle and hip joint kinematic strategies at toe-off and during the recovery phase. Similarities were evident in the initial configuration and peak flexion of the knee joint used by the fastest and slowest athlete. Although a greater (*p<0.05*) peak ankle joint dorsi-flexion was achieved in the recovery phase of the fastest (130.8 ±4.9º) compared to the slowest steps (122.9 ±5.8º), similar knee and hip joint kinematics were evident for the recovery phase.

Table 3
Intra-limb kinematic measures of the fastest and slowest athletes and fastest and slowest individual steps for the recovery phase

	Athlete				Step			
	Fastest		Slowest		Fastest		Slowest	
Toe-off θA (º)*	124.0	±1.8	120.5	±1.6	129.2	±5.1	121.5	±2.4
Toe-off θK (º)	149.7	±2.6	151.2	±1.2	158.8	±6.0	151.8	±6.4
Toe-off θH (º)*	163.9	±1.9	182.9	±1.7	176.3	±6.4	185.0	±8.6
Peak Flex θA (º)*#	124.0	±3.5	120.7	±4.2	130.8	±4.9	122.9	±5.8
Peak Flex θK (º)	59.1	±1.3	50.4	±4.0	45.4	±5.7	53.2	±5.5
Peak Flex θH (º)*	149.3	±3.3	155.5	±1.4	152.2	±4.9	156.9	±4.6
Peak Flex ωA (rad.s^{-1})*	5.0	±1.0	-3.9	±0.3	3.4	±1.4	-3.9	±1.4
Peak Flex ωK (rad.s^{-1})*	15.8	±0.4	-16.8	±0.5	16.2	±1.1	-16.6	±1.4
Peak Flex ωH (rad.s^{-1})*	10.4	±0.4	-9.1	±0.7	7.5	±1.1	-9.5	±0.3

θA θK θH = ankle, knee and hip joint configurations, respectively; Flex = flexion; ωA, ωK, ωH = ankle, knee and hip joint angular velocity, respectively. *Significant difference between fastest and slowest athletes at p<0.05; #Significant difference between fastest and slowest individual steps at p<0.05.

DISCUSSION: An examination of the underlying kinematic strategies defining sprint running performances was undertaken in order to extend insight into how a performance is physically and locally produced. The between athlete analyses highlighted diverse ankle, knee and hip

joint kinematic strategies between the fastest and slowest athlete for multiple step cycles and the distinct stance and recovery (early swing) phase. The use of a more extended ankle and knee at touchdown, and a slower peak joint extension in stance by the fastest athlete may be reflective of a superior ability to prevent lower limb collapse during stance compared to the slowest athlete. In contrast, the use of a similar knee joint configuration and less extended hip joint at toe-off by the fastest compared to the slowest athlete partially supported Hunter et al.'s (2005) suggestion that extra extension of the stance leg at takeoff (toe-off) may not necessarily benefit the generation of propulsion, and possibly more successful sprint performances. The between athlete differences in the ankle and hip joint configurations and peak angular velocities generated throughout the recovery phase may however suggest that the preferred action of the free limb's ankle and hip joint early in flight may distinguish a more successful sprint athlete. The typical diversity in intra-limb kinematics produced between athletes in the recovery phase, which has typically received limited attention in biomechanical studies of sprint running, further advocated consideration of the free leg mechanics as potential key contributors to sprint running performance.
The step-based analyses demonstrated that the slowest steps were distinguished by a more dorsi-flexed ankle early in swing compared to the fastest steps. Novacheck (1998) similarly highlighted that faster running gait modes had been characterised by less dorsi-flexion in the swing phase. The step-based intra-limb kinematics were however typically robust and suggested a commonality, particularly in the knee and hip joint strategy used to generate the fastest and slowest performances. More successful steps were therefore less readily defined by the local kinematic strategy employed when compared to athlete performances. Examination of athlete-specific, individual step performances may subsequently be advocated to distinguish determinants of superior step performances. The move towards more sensitive analyses, in preference to the traditionally used group investigations supported the recent endorsement by Salo et al. (*in press*) for individual athlete analyses in understanding sprint running performance. The diverse strategies employed by the fastest and slowest athletes however supported the continued use of more robust analyses when gaining insight into mechanical determinants of superior sprint performers.

CONCLUSION: The intra-limb kinematic strategies employed in the stance and recovery phase of multiple sprint running steps may uniquely define more successful sprint running athletes. A more sensitive individual athlete assessment may be required in order to establish local mechanical determinants of more successful, independent step performances.

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