Intralimb Joint Coordination Patterns of the Lower Extremity in Maximal Velocity Phase Sprint Running

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This study aimed to develop insight into the lower extremity joint coupling motions used in the maximal velocity phase of sprint running. Two-dimensional coordinate data were used to derive sagittal plane joint angle profiles of sprint running trials. Intralimb joint coupling motions were examined using a continuous relative phase (CRP) analysis. The knee-ankle (KA) coupling was more out of phase compared with the hip-knee (HK) coupling across the step phase (mean CRP: KA 89.9°; HK 34.2°) and produced a lower within-athlete CRP variability (VCRP) in stance. Touchdown (TD) produced more out-of-phase motions and a larger VCRP than toe-off. A destabilization of the lower extremity coordination pattern was considered necessary at TD to allow for the swing-to-stance transition. The key role that the KA joint motion has in the movement patterns used by healthy athletes in the maximal velocity phase of sprint running was highlighted.

Keywords: kinematics, step, stance, recovery, variability, touchdown, toe-off

Sprint running, which is an integral component of the majority of athletic movements, involves an initial acceleration phase followed by a phase of maximal velocity running. Each phase of a sprint comprises multiple steps, which are defined by a period of time in which the touchdown leg is in contact with the ground (stance) and then recovering in swing before the contralateral limb contacting the ground. The level of interaction between the spatiotemporal outcome measures of step length and step frequency has traditionally been discussed as the major biomechanical determinant of maximal velocity running (Hay, 1994; Hunter et al., 2004a). However, consideration of the task outcome alone provides an incomplete analysis of human movement (Heiderscheit, 2000). Understanding of the associated movement patterns (joint and limb kinematic profiles) used in sprint running is potentially fundamental in gaining a full insight into the technique developments required to enhance performance. Krell and Stefanyshyn (2006) further suggested that lower body kinematics play an important role in sprint running but confirmed that the contribution of each lower limb joint to performance remains unclear.

The kinematics of the stance leg are thought to play a major role in developing the propulsive ground reaction force generated in each step, which directly influences sprint performance (Hunter et al., 2004b). The hip and knee flexion-extension angular velocities of the stance leg have been considered to be particularly influential in generating large propulsive ground reaction forces in the acceleration phase of sprint running (Hunter et al., 2004b). Novacheck (1998) further highlighted that increases in sprint running velocity have been associated with increases in maximum hip flexion, which resulted in a longer step length. Although the contribution of the swing phase to propulsion in sprint running remains largely unknown (Hunter et al., 2005), running velocity increases have also been associated with increases in knee joint flexion (Novacheck, 1998), which are maximal early in the swing (recovery) phase of a step.

While examining individual joint kinematics has provided valuable insight into sprint running mechanics, limited insight into the interaction of joints exists. Novacheck (1998) suggested that compensatory effects in the ankle and hip joints by healthy runners occur in response to minimal knee joint extension changes in the second phase of stance. Krell and Stefanyshyn (2006) later highlighted that a necessary component of sprint running velocity generation was a plantar flexion of the ankle and a corresponding knee joint extension just before takeoff. The notion that the movement patterns used in sprint running may be determined by a combination of segment interactions, or joint couplings was recently acknowledged by Hunter et al. (2005) but limited understanding of the joint coupling motions defining sprint running currently exists. Pohl et al. (2007) highlighted that inconsistencies exist between the coupling motions of walking and running, which limits the subsequent coupling motions that may be assumed for sprint running. Dierks and Davis (2007) further highlighted that insight into what constitutes “normal” joint coupling in the gait of healthy individuals remains limited. Insights into the lower limb joint coupling motions of sprint running stance and swing are subsequently warranted to enhance
understanding of healthy gait and the task-specific movement patterns defining high-level athletic performance. Previous studies using coordination analyses such as the continuous relative phase (CRP), to examine coupling motions in running have traditionally focused on the potential association to overuse injury risk in distance running (DeLeo et al., 2004; Heiderscheit et al., 2002; Hamill et al., 1999). The CRP approach has been advocated in previous studies of running mechanics due to its ability to obtain a continuous measure of coupling throughout a gait cycle and to provide information regarding the stability and flexibility of a movement pattern (Hamill et al., 1999). To gain a better understanding about “normal” coupling patterns during running, Dierks and Davis (2007) used a CRP analysis to examine joint coupling patterns in healthy distance runners. The authors found that the out-of-phase couplings associated with the transition events at heel strike and toe-off during the running steps were considered to be related to a less stable state (Scholz, 1990) and the subsequent ability of the system to change from one coordinative state to another.

Within other athletic disciplines, joint coordination and coordination variability analyses have successfully been employed to gain insight into the movement strategies underlying performance (e.g., Wilson et al., 2008). Variability in kinematic measures has emerged as an important variable by which to describe coordinative changes (Seay et al., 2006). Variability has been suggested to have a functional role in movement execution (Hamill et al., 1999; Li et al., 1999) but conflicting suggestions exist regarding the contribution of movement variability to locomotion. While variability has been associated with a decrement in locomotive performance (Dierks & Davis, 2007), joint coordination variability has been suggested to allow a beneficial change in the coordination pattern (Heiderscheit et al., 2002). High variability in lower extremity joint coupling motions has favorably been associated with healthy runners when compared with runners presenting with an overuse injury (Hamill et al., 1999). The use of a more variable coupling motion was suggested to potentially reduce the stress placed on the lower extremity structures. Bradshaw et al. (2007) further suggested that a flexible coupling motion pattern is associated with high-standard performance in a physical task such as the sprint running start. However, limited insight into the variability of both task and intralimb kinematic measures associated with sprint running currently exists.

An examination of the intralimb coupling motions in sprint running is potentially valuable in enhancing understanding of the typical kinematic movement patterns employed. Unlike previous studies examining single joint or limb kinematics in sprint running, this study aimed to develop insight into the intralimb joint coupling motions used during the stance, early-swing (recovery) and entire step phase of maximal velocity phase sprint running (MVSPR). The study quantified the phase-specific CRP and CRP variability to examine the sagittal plane joint coupling motions of the lower extremity. It was hypothesized that an out-of-phase CRP would exist in the transitions between stance and recovery and the requirement for a coordination change during the distinct transition events would be associated with phase- and coupling-specific changes in the CRP variability.

Methods

Subjects

Six university-based male athletes (mean ± SD age: 20.2 ± 0.8 years; mass: 73.48 ± 7.49 kg; height: 1.807 ± 0.051 m) who competed in sprint running events (100 m, 200 m and 400 m) were recruited for the study. The athletes were declared healthy and injury free at the onset of the data collections. Ethical approval for the data collection was obtained from the University’s Research Ethics Committee and each subject gave written informed consent before the onset of the data collections.

Protocol

Following a self-selected warm-up, each athlete completed four sprint running trials on a 110-m Mondo running track situated within a national indoor athletics center. Running trials were performed over an approximate distance of 70 m from a standing start and subjects were asked to maintain a constant sprint running velocity for as long as possible following acceleration. Subjects wore clothing suitable for sprint training and their own spiked shoes for each running trial. A rest period of up to 5 min was permitted between trials.

Data Collection and Processing

A Cartesian optoelectronic dynamic anthropometer (CODA, 6.30B-CX1) motion analysis system was used to obtain three-dimensional (3-D) coordinate data (sample rate: 200 Hz) of active markers comprising light-emitting diodes during the maximal velocity phase of the sprint running trials. Markers were secured to the lateral aspect of the spiked shoe at the distal end of the fifth toe, and on the left side of the body at the ankle, knee, hip and shoulder joint centers. Markers were additionally located on the medial aspect of the right leg at the distal end of the first toe and at the ankle and knee joint centers. Two coaligned CODA (6.30B-CX1) scanners were located 6 m apart along the longitudinal axis of the running track and 4.2 m from the center of the running lane. A subsequent field of view of 10 m was produced in the direction of the running trials between 40 m and 50 m. The inclusion or rejection of a trial was ascertained by the extent of marker visibility. The raw coordinate data of the accepted trials were low pass filtered, using a fourth-order Butterworth filter with a cut-off frequency of 15 Hz.

Data Analysis

Consecutive initial foot-ground touchdown (TD) events of the left and right lower limbs defined individual steps
within each selected trial. The examination of multiple
within trial steps in this study precluded the collection of
force data for individual steps but was considered to allow
and a realistic replication of “normal” sprint running due to the
reduced effects of force plate targeting. Previous research
by Hunter et al. (2004a) identified that ground contact
events in sprint running could be determined to within one
field (sample rate: 200 Hz) of force-derived events using
the vertical acceleration displacement of a toe marker. The
kinematic approach used in this study was subsequently
considered to provide a realistic representation of ground
contact events for the step phase definitions. Touchdown
events were established using two simultaneously applied
kinematic criterion measures: the establishment of a peak
in the second derivative of the vertical (z) displacement,
which was previously used by Hunter et al. (2004a) and
Hreljac and Marshall (2000), and a z-displacement of less
than 60 mm in the respective left and right toe markers.
Ground contact events, such as TD and toe-off (TO), have
traditionally been well defined using force plate data due
to the single steps examined in each trial.

A single step was defined between contralateral foot
TD events and the velocity of each step was determined
as the product of the step length (anterior-posterior
(y) displacement between consecutive TD events) and
step time (duration between consecutive TD events).
A minimum of three steps were obtained for each trial
and the trial-specific velocities of successive steps were
examined to ensure that athletes were not progressively
accelerating during the data collection volume. Two steps
with a left leg TD were subsequently selected from each
trial and further subdivided into a stance (left leg TD to
left leg TO) and recovery (left leg TO to right leg TD)
phase (early swing phase). The instant of TO was estab-
lished for the selected steps (N = eight athlete-specific
steps) as the first time following TD that the left toe
z-displacement matched or exceeded the corresponding
left toe z-displacement at TD.

Sagittal plane joint angles for the left leg ankle
(plantar–dorsiflexion), knee (flexion–extension) and hip
(flexion–extension) were derived for each analyzed step
using the raw, joint center coordinate data, which were
generated from the 3-D CODA recordings as projections
onto the y-z plane. A cubic spline was fitted to each joint
angle time profile to obtain smooth continuous first
derivatives (velocity time profiles). The step-specific
angular data were interpolated to 100 points and subse-
duently normalized to 100% of the respective step time.

The intralimb joint coupling motions were assessed
for each step using a CRP analysis, which was calculated
using the angular position and velocity profiles of the relation-
ship between the joint actions (Dierks & Davis, 2007).
A phase portrait was created by plotting the normalized
joint angle (abscissa) against the respective normalized
joint angular velocity (ordinate axis). The joint angle and
angular velocity were normalized to the maximum and
minimum of the athlete-specific data set according to the
procedure presented by Hamill et al. (1999). Hamill et
al. (2000) advocated the normalization of each oscillator
(joint angle profile) for intralimb coordination analyses to
adjust for amplitude differences in the range of motion of
the oscillator and to center the phase plot about an origin.
Peters et al. (2003) further supported the normalization of
the phase plane in CRP analyses of running gait to
account for the potential nonsinusoidal profiles associated
with the lower limb motions used in running.

As detailed in Hamill et al. (2000), phase angles
comprising a range 0–180° were determined as the
four-quadrant arctangent angle formed between the right
horizontal and the line from the origin to the respective
data point formed by the phase portrait. The CRP time
histories for the sagittal plane KA and HK joint couplings
were determined by quantifying the difference between
the phase angle of the distal and proximal joint at each
time interval. Athlete-specific ensemble time histories
for the CRP and within athlete variation of CRP were
determined across all athlete-based steps using the mean
CRP and associated standard deviation (SD) respectively
at each time point. Time histories for the group ensemble
CRP and within athlete variation (VCRP) were deter-
mined as the average across each time point of the athlete-
specific CRP and within athlete CRP ensemble profiles,
respectively (N = six athletes). The group mean CRP
and VCRP were calculated for the stance, recovery and
whole step phase as the average of the group ensemble
absolute CRP and VCRP curves, respectively over the
phase-related time periods.

A Friedman two-way analysis of variance by ranks
test was used to statistically compare the KA and HK
CRP, and the KA and HK VCRP time history profiles
and discrete step events. The locations of significant
differences in the continuous and discrete parameters
were established using a Wilcoxon matched-pairs test.
A statistical comparison of within coupling differences
between the TD and TO events was also made using a
Wilcoxon matched-pairs test. Statistically significant
differences were identified at p < .05

Results

The group ensemble step profiles (± between-athlete
SD) for the ankle, knee and hip joint angle and angular
velocity are illustrated in Figure 1. The individual step-
based joint angle and angular velocity profiles were used
to derive intralimb joint coupling motions for the lower
limb, which are illustrated in Figure 2a as group ensemble
(± between-athlete SD) KA and HK CRP profiles for
the entire step phase. Individual step TO times were used
to divide the respective step phase into stance and recovery.

Figures 1 and 2 illustrate the group ensemble profiles
with stance and recovery distinguished by the group
mean TO time (group mean ± SD: 34.6 ± 4.0% of
the step time). Similar mean step velocities were achieved
by the athletes across all analyzed steps (group mean ±
SD: 8.567 ± 0.353 m·s⁻¹).

The two couplings displayed differing amounts of
relative phase at the onset of the step, with the KA cou-
ping being more in phase than the HK coupling (Figure
Unlike the HK coupling, which tended toward more in phase motion immediately after TD, the KA coupling became more out of phase resulting in a peak CRP of 162.59° at 19% of the step time. During mid to late stance, both intralimb couplings tended toward a more in phase motion. The mid to late recovery phase was dominated by the progression of a more out-of-phase KA coupling while the HK coupling remained relatively more in phase.

The KA coupling produced a significantly larger group mean CRP and subsequent more out-of-phase motion (mean CRP: 89.82°, \( p < .01 \)) across the step phase duration compared with the HK coupling (67.71°) (Figure 3). The TD event incurred a significantly (\( p < .01 \)) more out-of-phase motion across the lower extremity couplings than achieved at the respective athlete’s midstep TO event (Figure 4).

The progression toward a more in phase motion by each intralimb coupling during early recovery was accompanied by a high VCRP (Figure 2b) in the KA and HK couplings. As illustrated in Figure 3, the larger mean step phase CRP produced by the KA was associated with a significantly lower mean VCRP (6.70°, \( p < .05 \)) across stance than the HK (7.05°) coupling. Although, there was a tendency for a larger VCRP at TD compared with TO for both of the couplings (Figure 4), the between event difference was not significant across the lower extremity couplings.
Discussion

The intralimb joint coupling motions of the lower extremity were examined for the stance, recovery and entire phase of MVSR steps. The study supports a growing body of literature into sprint running and similar to recent research (Bezodis et al., 2008), aimed to characterize the mechanics of MVSR in well-trained and asymptomatic athletes. Unlike previous studies (e.g., Hunter et al., 2004b), which have focused on individual joint kinematic analyses, the study aimed to develop insight into the coupling motions defining MVSR. Understanding of the joint coupling motions used in each phase and throughout the entire step cycle was considered valuable for enhancing insight into the “normal” movement patterns defining high-level athletic performance sprint running.

It was hypothesized that the CRP of the KA and HK coupling motions would be out of phase in the transitions from stance to swing. The CRP analysis partially confirmed the hypothesis by demonstrating that the step phase of the sprint running trials was initiated with out-of-phase KA and HK coupling motions, which were followed by the progression toward more in phase motions approaching TO. Out-of-phase motion has previously been considered to reflect a less stable coordinative state (Scholz, 1990) and has previously been associated with transitions in the gait cycle (Hamill et al., 1999; Dierks & Davis, 2007). The out-of-phase motion of the lower limb (KA and HK) couplings at TD may therefore be attributed to the need to destabilize the lower extremity coordination strategy, to allow for a subsequent transition from open chain recovery to closed chain stance. In contrast, the more in phase...
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Figure 3 — Group mean CRP (columns) and VCRP (points) for the KA and HK joint couplings during the stance, recovery and entire step phase. Median (interval for 95% confidence levels) values are presented below the abscissa axis. Significant difference between KA and HK CRP for step, stance and recovery phases ($p < .01$); significant difference between KA and HK VCRP for step and stance phases ($p < .05$).

Figure 4 — Group mean CRP (columns) and VCRP (points) for joint couplings at touchdown (TD) and toe-off (TO) during the step phase. Median (interval for 95% confidence levels) values are presented below the abscissa axis. Significant difference between CRP of couplings at TD and TO ($p < .05$).

couplings at TO suggested the presence of a more stable coordinative state during the stance to recovery transition of MVSR than occurring in the transfer between recovery and stance. A larger net knee joint torque has previously been suggested during the gait transition from swing to stance compared with stance to swing (DeVita, 1994). A high knee joint torque at TD was further suggested to be necessary to counter possible knee flexion in weight acceptance during the acceleration phase of sprint running trials (Johnson & Buckley, 2001). The less stable coordinative state (more out-of-phase motions) associated with the transition from recovery to stance (TD) in the MVSR steps may therefore be associated with a relatively more active musculature controlling the knee joint than achieved in the stance to recovery transition (TO). Examination of the relationship between joint coupling motions and the respective joint torque profiles is however warranted to confirm the role of the knee joint in destabilizing the lower limb couplings in MVSR step transition events.
In distance running, more out-of-phase lower extremity coupling motions have been associated with transition events and a subsequent switch to a new coordination pattern such as that required in reorientating the foot at TO (Diers & Davis, 2007). In comparison with the TO event, TD in the sprint running step requires greater demands on the lower extremity, as reflected by the findings of DeVita (1994), to attenuate a rapidly occurring impact and braking force. Thus, the significantly more in phase lower extremity couplings associated with TO compared with TD may be indicative of a transition event with no shock attenuation demands. In contrast to distance running, the forefoot ground contact maintained in sprint running potentially reduces the necessary amount of reorientation of the foot at TO and may therefore further explain relatively more in phase intralimb couplings at TO compared with TD.

Unlike the HK coupling, which typically became more in phase during early stance the KA coupling advanced toward a more out-of-phase peak in the CRP profile during midstance (Figure 1a). Abrupt changes in coordination patterns have previously been attributed to phase transitions (Hamill et al., 1999). The movement toward antiphase motion in the KA coupling in midstance may be attributed to a reversal in direction by one joint in the coupling to allow a change in the coordination pattern for the transition from braking to propulsion. As illustrated in the individual joint angle profiles (Figure 1a) midstance was associated with a rapid transfer between ankle joint dorsiflexion and plantar flexion. The KA coupling pattern associated with midstance may subsequently be attributed to an abrupt change in the ankle relative to the knee joint angular velocity (Figure 2b) causing the phase angles of the knee and ankle to behave dissimilarly during this phase. The fluctuation in the KA CRP profile during midstance may subsequently be reflective of the movement pattern required to achieve the braking-propulsion transition in MVSIR.

Continuous relative phase variability has been considered a valuable measure to understand coordination changes in locomotion (Seay et al., 2006) and has provided important insights into the movement patterns associated with athletic movements (Wilson et al., 2008). The within athlete CRP variability in the intralimb coupling motions associated with the MVSIR trials was additionally examined in this investigation. A phase- and coupling-specific CRP variability was hypothesized to be required to allow a coordination change at the distinct transition events in the step cycle. Although the variability of the two coupling motions was similar across the step phase, the more out-of-phase motion of the KA coupling during the step phase was associated with a lower variability than the HK coupling in stance. The more consistent KA coupling motion suggests that, in comparison with the HK coupling, the well-trained, healthy sprinter performing in a predictable environment uses a more reproducible KA coupling motion. Velocity generation in MVSIR may therefore be constrained by the use of an underlying mechanism that maintains an invariant KA kinematic strategy. More combinations of the HK coupling action may contrastingly be employed to produce a similar MVSIR outcome. A lower CRP variability has been suggested to be an indicator of a nonhealthy state (Hamill et al., 1999). The more consistent nature of the KA compared with the HK coupling motion may further suggest a greater predisposition of the knee and ankle joints to overuse injury compared with the hip during MVSIR due to a constant localized stress being placed on the knee and ankle joints. Previous studies comparing coupling motions in walking and moderately paced running have suggested that lower extremity interlimb movement patterns are more sensitive to perturbations than intralimb patterns (Seay et al., 2006). Although not addressed in this study, changes to the interlimb couplings between steps may more readily assist the development of sprint running performance than achieved by perturbing the KA complex. Future research examining interlimb joint coupling motions could therefore provide a further valuable insight into the movement patterns defining MVSIR.

Opposing views of variability in the assessment of task and joint coordination responses currently exist (Heiderscheit et al., 2002) such that variability in intralimb couplings may alternatively be required to achieve a consistent task outcome. This study was limited to a descriptive assessment of the joint coupling motions used in MVSIR without consideration of the nature and variability of the movement outcome i.e., the spatial and temporal measures of the step. Examination of the association between joint coupling motions and the variability of the end-effector of sprint running is warranted to further develop insight into the movement patterns defining MVSIR performance. Furthermore, a comparative study of the joint coupling motions used in distinct sprint running phases, such as acceleration, maximal velocity and deceleration, is potentially valuable in fully understanding the mechanical determinants of performance.

As highlighted by Bezodis et al. (2008) studies of sprint running mechanics have typically examined athletes of varying ability. The low athlete and step sample size analyzed in this study was attributed to the requirement of gaining an understanding of the mechanical indicators associated with maximal velocity generation in well-trained, healthy athletes only. The use of a larger sample size of subelite and elite athletes and steps is however warranted in future studies to confirm the joint coupling motions reported in this investigation and to provide a more extensive insight into “normal” sprint running movement patterns by allowing detailed within and between athlete assessments.

This study aimed to develop the limited understanding of the interaction of lower limb joint motions in MVSIR. The key role that the knee-ankle sagittal plane coupling motion has in the step phase movement patterns used by healthy, well-trained athletes was highlighted. Future research aims to use the insight gained to examine the association between intralimb coupling motions and end-effector responses in sprint running.
References


