*International Journal of Sports Physiology and Performance,* (Ahead of Print)
https://doi.org/10.1123/ijspp.2021-0107

Human Kinetics
ORIGINAL INVESTIGATION

# Can We Modify Maximal Speed Running Posture? Implications for Performance and Hamstring Injury Management

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***Purpose:*** Sprint kinematics have been linked to hamstring injury and performance. This study aimed to examine if a specific 6-week multimodal intervention, combining lumbopelvic control and unning technique exercises, induced changes in pelvis and lower-limb kinematics at maximal speed and improved sprint performance. ***Methods:*** Healthy amateur athletes were assigned to a control or intervention group (IG). A sprint test with 3-dimensional kinematic measurements was performed before (PRE) and after (POST) 6 weeks of training. The IG program included 3 weekly sessions integrating coaching, strength and conditioning, and physical therapy approaches (eg, manual therapy, mobility, lumbopelvic control, strength and sprint "front-side mechanics"-oriented drills). ***Results:*** Analyses of variance showed no between-group differences at PRE. At POST, intragroup analyses showed PRE–POST differences for the pelvic (sagittal and frontal planes) and thigh kinematics and improved sprint performance (split times) for the IG only. Specifically, IG showed (1) a lower anterior pelvic tilt during the late swing phase, (2) greater pelvic obliquity on the free-leg side during the early swing phase, (3) higher vertical position of the front-leg knee, (4) an increase in thigh angular velocity and thigh retraction velocity, (5) lower between-knees distance at initial contact, and (6) a shorter ground contact duration. The intergroup analysis revealed disparate effects (possibly to very likely) in the most relevant variables investigated. ***Conclusion:*** The 6-week multimodal training program induced clear pelvic and lower-limb kinematic changes during maximal speed sprinting. These alterations may collectively be associated with reduced risk of muscle strain and were concomitant with significant sprint performance improvement.

***Keywords:*** pelvic tilt, sprint performance, sprint kinematics, hamstring strain, sprint mechanics, front-side mechanics

Hamstring strain injuries (HSI) remain highly prevalent and represent a significant burden in sports involving high-speed running (HSR).[1–4] Despite eccentric focused strength training having been consistently proposed as a successful prevention method, HSI rates have not improved over the last 40 years.[3,4] Contrary to what has been done in other pathologies, such as anterior cruciate ligament[5] or groin pain,[6] no studies have been published in which the main injury mechanism has been biomechanically corrected. Thus, there is a need to explore variables other than eccentric strength, including factors such as sprinting mechanics that can potentially influence the mechanism of injury.

Anterior pelvic tilt (APT) has been reported to be closely related to the moments where the hamstring muscle-tendon tissues face the highest mechanical strain during sprinting.[7] Theoretically, a greater APT would superiorly translate the ischial tuberosity, resulting in a greater active lengthening and passive tension demand of the posterior thigh musculature due to a greater moment arm derived from the relative hip flexion generated.[8] The aforementioned arguments may explain the association found between APT and HSI risk in different prospective studies.[8,9] Assuming that, during maximal speed sprinting, the biceps femoris (BF) faces a greater elongation at the proximal level,[10] the level of strain experienced may be directly influenced by the APT magnitude, among other factors. Thus, it seems logical to expect that, anatomically, a decrease in APT would reduce the tensile strength of the proximal region of the most injured muscle (ie, BF) during HSR.

Recently, we showed a change in pelvic kinematics (ie, APT decrease) during walking after 6 weeks of a multimodal training intervention (manual therapy, mobility, lumbopelvic control, and strength) specifically designed to correct and decrease APT and associated lumbar lordosis.[11] However, it is necessary to test whether this program would be efficient when transferred to sprint-specific APT, since during sprinting, similar hip extension but greater pelvic anteversion and lumbar lordosis are observed compared with walking.[12]

A widely accepted technical model of sprinting, known as "front-side mechanics," describes how a specific posture or kinematics anterior to the center of mass are associated with better sprint performance.[13] Specifically, front-side mechanics seek to maximize leg motions occurring in front of the vertical torso line while minimizing actions occurring behind that line throughout the

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sprint cycle.[13] With specific focus on maximum speed sprinting, this technical model is characterized by maintaining an upright trunk and a neutral pelvic position that allows one to reach a higher knee lift position during the swing that would allow a subsequent active leg motion to "punch" the swing leg into the ground as well as a reduced touchdown distance (TDd), resulting in lower braking anteroposterior and higher vertical components of the ground reaction forces (GRF).[13–15] This would allow for higher overall stiffness and reduced stance duration, which have been associated with greater maximal sprinting speeds.[15] However, this technical model and accompanying coaching emphasis on front-side mechanics have been primarily based on descriptive comparisons of elite and subelite athlete's kinematics.[13] To our knowledge, no scientific evidence has supported the possibility of altering sprint kinematics after a specifically designed training program aimed at improving front-side mechanics, pelvic and trunk position, and in turn, maximal sprint speed.

Therefore, the aim of the present study was to examine if a specific 6-week multimodal intervention combined with an on-field running technique program induced changes in pelvis and lower-limb kinematics at maximal speed. Based on our recent study showing changes in APT during gait locomotion[11], we hypothesized that the multimodal training program (lumbopelvic control exercises + sprint technique training) proposed in this pilot study would induce a decrease in APT together with changes in other biomechanical variables during the maximum running speed phase of the sprint toward a more "front-side"-oriented sprint technical model, characterized by a more upright trunk position, a higher maximum vertical knee position during swing phase, and lower between-knees distance with shorter TDd at initial contact.

# Methods

## Study Design

We conducted a prospective comparative trial, with testing sessions separated by a 6-week period comprising an intervention program only for IG. The present study was approved by the University of Bath Health Department Ethics Committee (EP 18/19 027) in agreement with the Declaration of Helsinki.

## Population

Athlete recruitment was made based on the following inclusion and exclusion criteria: participants regularly practiced sports involving sprinting (at least 3 times per week), none of the athletes had previous experience in the specific sprint technique training, and none of the athletes had sustained any lower-limb or lumbopelvic injury that might impact running mechanics during the 12 weeks prior to the intervention.

Fifteen amateur men athletes (1.79 [0.75] m, 77.0 [7.6] kg) were recruited and gave their written informed consent to participate in this study. The athletes were assigned in a counterbalanced way according to the initial sprint performance into 2 groups: 8 athletes in the control group (CG; 1.78 [0.03] m, 78.9 [5.8] kg) and 7 athletes in the intervention group (IG; 1.79 [0.07] m, 75.9 [9.0] kg).

## Testing Procedures

All tests were conducted at the same time of day, from 12:00 PM to 4:00 PM. During both assessments, the subjects were asked to wear a pair of loose shorts and training shoes. For each session, the warm-up consisted of 5 minutes of jogging at a self-selected pace, followed by 5 minutes of sprint-specific muscular warm-up dynamic exercises, 2 progressive sprints separated by 3 minutes of passive rest, and two 10-m flying sprints. After the warm-up, markers were placed for the 3-dimensional kinematics data collection.

Once the warm-up and static calibration were completed, the participants were asked to maximally sprint twice for 35 m, with a 4-minute recovery between efforts. During these attempts, the kinematic data of at least 1 full stride during the maximum speed phase and the sprint times were collected. The Qualisys Track Manager software® (Qualisys AB, Gothenburg, Sweden) was used to record the marker positions during the sprint trials, which was used alongside a single-beam timing system (Brower timing, Draper, UT). Photoelectric cell gates were placed at 0, 5, 10, 15, 20, 25, and 35 m in order to assess maximal running speed capabilities.

## Equipment and Data Acquisition

Three-dimensional kinematics were recorded using 15 optoelectronic motion analysis cameras (250 Hz; Oqus, Qualisys AB) with the sample frequency set at 200 Hz. The cameras were strategically placed on tripods of different heights between 24 and 36 m of the indoor athletics track. An overview of the described setup can be found in Supplementary Material 1 (available online). Prior to the data collection, the capture volume of approximately 10 × 1.1 × 1.5 m was calibrated according to the manufacturer's guidelines. Twenty-four markers were placed bilaterally on the following lower-limb landmarks: posterior superior iliac spine, anterior superior iliac spine, greater trochanter, medial and lateral femoral condyles, medial and lateral malleoli, heel, first and fifth metatarsophalangeal joints, and the hallux. Additionally, rigid clusters of 4 markers were attached to the thigh and shank segments.

A static calibration trial was used to allow a kinematic model of each athlete to be constructed. Subsequently, the medial femoral condyle, medial malleolus, and greater trochanter markers were removed for the dynamic trials.

## Data Processing

Following labeling and gap filling of trajectories (Qualisys Track Manager, version 2019.3; Qualisys AB) the data were exported to Visual 3D (version 6; C-Motion Inc, Germantown, MD), where the raw trajectories were low-pass filtered (Butterworth second order, cutoff 12 Hz derived through residual analysis). Three-dimensional lower-limb joint angles (hip, knee, and ankle) of the ipsi- and contralateral limb were computed as the orientation of the distal segment compared with that of the proximal segment using a *X*–*Y*–*Z* Cardan sequence. Similarly, segment orientations (pelvis, thigh, and shank) were computed as the orientation of those segments compared with the global coordinate system. Derivatives of the filtered marker positions were computed using a finite central differences method, and touchdown and toe-off events were computed following the method described by Handsaker et al.[16] Seven key events were then identified in each stride collected for every sprinting trial and used in subsequent statistical analysis: toe-off, maximal hip extension, maximal vertical knee displacement, maximal vertical projection, maximal hip flexion, touchdown, and full support. Each event was defined according to specific criteria: the time at which contact with the ground is lost for the ipsilateral leg (toe-off); the time for maximum hip extension for the ipsilateral leg (maximal hip extension); time for maximum hip flexion for the swing leg (maximal hip flexion); time at which maximum distance on the vertical axis is achieved for the swing-leg knee (maximal vertical knee displacement); and maximum distance on the vertical axis for the center of the pelvic segment (maximal vertical projection); the end of aerial phase (touchdown); and the time where lateral malleolus for support leg is underneath the pelvis segment center (full support). The maximum instantaneous horizontal velocity of the pelvis segment was also extracted as a proxy measure of the maximum center of mass velocity.

## Kinematic Parameters

During the captured stride cycles, relevant dependent variables for the ipsi- and contralateral leg were selected for the subsequent analysis, such as joint angles or segment orientations. Additionally, TDd, defined as the distance between the vertical projection of the center of the pelvic segment and the nearest contact zone at touchdown; the distance between knees (DBK) at touchdown; maximum knee height; and ground contact times were considered for the analysis as discrete variables.

## Intervention: Multimodal Training

The athletes in CG were requested not to modify their established training routines during the entire 6-week period.

The athletes in IG underwent a multimodal training program composed of 3 sessions per week for 6 weeks. The training program included coaching, strength and conditioning, and physical therapy components. The full training program is provided in the Supplementary Material 2 (available online) (written description) and Supplementary Material 3 (available online) (video overview). The IG athletes were not allowed to continue their usual training during the intervention.

## Statistical Analysis

Kinematic data waveforms were temporally normalized across a single stride cycle (touchdown to touchdown). Statistical parametric mapping (SPM) 1D open-source software was then used to evaluate the influence of a multimodal training approach using an SPM 1D paired *t* test establishing the critical threshold at $\alpha = .05$. If the SPM{t} curve exceeded this critical threshold when comparing the postassessment data, the kinematics were deemed to be significantly different from the pretest at these specific nodes. The data from all successfully collected strides were used for the analysis.

To obtain a more general picture of the effects of the intervention and to minimize possible distortion caused by temporal normalization, a discrete analysis of the kinematic variables was also performed in JASP (version 0.12.2, Amsterdam, Netherlands) for the key events described above.[17,18]

Values were reported as mean (SD). Statistical significance was established at the $P < .05$ level. Independent sample *t* tests were conducted to examine intergroup differences at PRE (before 6-wk period), whereas paired sample *t* tests were used to analyze intragroup changes between PRE and POST. Effect sizes (ESs) alongside CIs were calculated using Cohen *d* standardized differences. The effects were deemed to be practically meaningful if the 95% confidence interval did not cross zero (in either direction). Only results with $\text{ES} \geq 0.8$, this value being set as large, are highlighted in Supplementary Material 4 (available online) and then detailed in Supplementary Material 5 (available online).

The smallest worthwhile change (0.2 multiplied by the between-subject SD), based on the Cohen ES principle,[19] was used to calculate intergroup differences based on the difference experienced by both groups in the most representative variables of running kinematics. The chances of the quantitative effect were assessed qualitatively as follows: 0.05%, most unlikely; 0.5% to 5%, very unlikely; 5% to 25%, unlikely; 25% to 75%, possibly; 75% to 95%, likely; 95% to 99%, very likely; and 0.99%, most likely.

# Results

## Primary Outcome: Sprint Kinematics

No significant differences were found between groups at PRE when analyzing segments and joint curves by SPM or independent *t* test. Once the 6-week period was concluded (at POST), the intragroup SPM analysis revealed differences for the pelvic and thigh segments in the sagittal plane for the IG (Figure 1), while not for CG.

Additional discrete analysis for these variables revealed a large number of significant differences regarding the angle of the joints or the orientation of these segments at the defined key moments (see Supplementary Materials 4 and 5 [available online] for a detailed analysis). The differences for the most representative variables are summarized for better understanding in Figure 2 and visually recreated in Figure 3.

Furthermore, only the IG significantly decreased the DBK indicator of the amount of “leg recovery” at touchdown lower limit (LL) (PRE: 0.28 [0.06] m to POST: 0.16 [0.03] m; ES: −2.02 [LL: −3.34; upper limit (UL): −0.66]; $P = .002$); significantly increased the maximum knee height reached (PRE: 0.68 [0.06] m to POST:0.77 [0.08] m; ES: 3.05 [LL: 1.20; UL: 4.68]; $P < .001$), average thigh angular velocity during the entire gait cycle (PRE: 388.7 [17.6] $\text{deg}\cdot\text{s}^{-1}$ to POST: 411.7 [9.2] $\text{deg}\cdot\text{s}^{-1}$; ES: 1.13 [LL: 0.14; UL: 2.08]; $P = .029$), and average thigh angular retraction velocity (PRE: 301.8 [52.4] $\text{deg}\cdot\text{s}^{-1}$ to POST: 354.9 [50.3] $\text{deg}\cdot\text{s}^{-1}$; ES: 1.44 [LL: 0.33; UL: 2.51]; $P = .009$); and significantly reduced the ground contact time (0.109 [0.008] s to 0.102 [0.008] s; ES: −0.96 [LL: −1.85; UL: −0.03]; $P < .05$).

Kinematic intergroup differences for the most relevant kinematic variables can be observed in Figure 4.

## Secondary Outcome: Sprint Performance

No significant differences between IG and CG were found at PRE for any of the split times analyzed. The CG showed no significant differences for any of the split times between PRE and POST, whereas statistically significant decreases ($P < .05$) were found for 0 to 5 ($P = .013$), 5 to 10 ($P = .015$), 10 to 15 ($P = .049$), 25 to 35 ($P = .015$), 0 to 10 ($P = .011$), 0 to 20 ($P = .023$), and 0 to 35 ($P = .029$) split times in the IG group (Table 1).

# Discussion

The main findings of the present study validate our initial hypothesis and were, first, that 6-week multimodal intervention combining lumbopelvic control exercises with a running technique program induced significant changes in the sagittal and frontal plane kinematics of the pelvis at maximal speed. This resulted in a lower APT during the late swing phase and a higher pelvic obliquity on the free-leg side during the early swing phase. Similarly, the kinematics of the lower extremities were also modified according to the front-side mechanics principles, resulting in an increase in the maximum height

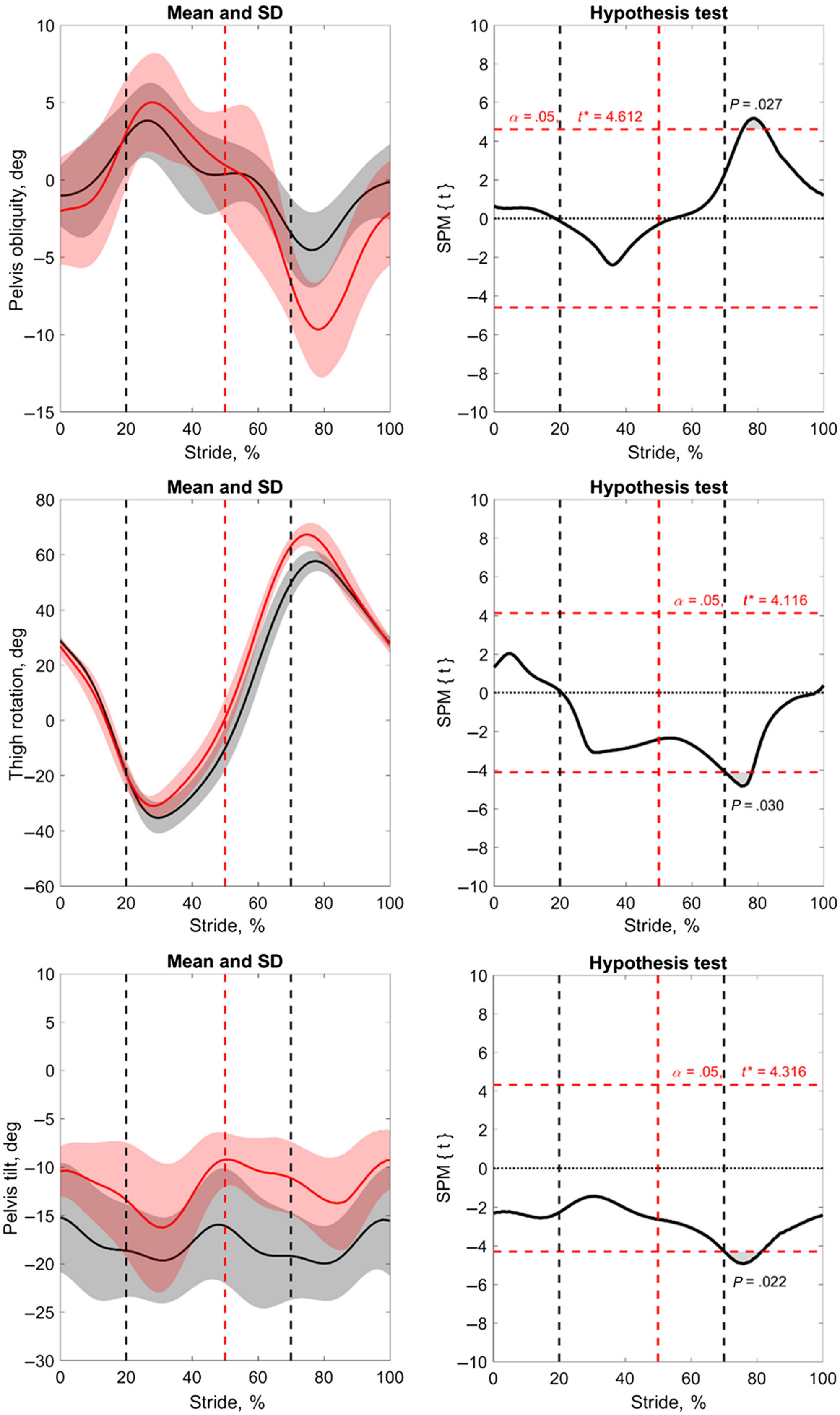

**Figure 1** — Pelvic tilt, pelvic obliquity, and thigh orientation in the sagittal plane on SPM analysis. Darker lines and shadows refer to mean and SD PRE values for the intervention group, lighter ones refer to POST values. Vertical dashed lines represent toe-off moments for both ipsilateral and contralateral limbs while vertical dotted ones indicate the touchdown of the next step. Horizontal lighter dashed lines represent the statistical significance threshold between both moments. IG indicates intervention group; SPM, statistical parametric mapping.

## APT across the sprint cycle

| | | TO, deg | MVP, deg | Late swing APT, deg | TD, deg |
|---|---|---|---|---|---|
| IG | PRE | −18.6 (5.2) | −16.7 (6.0) | −7.2 (9.0) | −15.1 (6.0) |
| | POST | −13.4 (6.4)* | −10.3 (4.8)* | −5.2 (6.2) | −10.2 (3.4)* |
| | Individual response | □□□□□■□ | □□□□□■□ | □□□□□■□ | □□□□□■□ |
| CG | PRE | −17.1 (5.4) | −14.7 (6.6) | −6.1 (7.8) | −12.4 (7.0) |
| | POST | −15.4 (8.2) | −13.0 (8.9) | −6.2 (8.5) | −14.1 (10.3) |
| | Individual response | ■□□■□■□■ | ■□□■□□□■ | ■□□■■■□■ | ■□□■□■■■ |

## Key technical parameters

| | | Contact time, s | MKVD, m | Mean thigh velocity, deg·s$^{-1}$ | Mean retraction velocity, deg·s$^{-1}$ | DBK at TD , m | TD distance, m |
|---|---|---|---|---|---|---|---|
| IG | PRE | 0.109 (0.01) | 0.68 (0.06) | 388.7 (17.6) | 301.8 (52.4) | 0.28 (0.06) | 0.29 (0.03) |
| | POST | 0.102 (0.01)* | 0.77 (0.08)** | 411.7 (9.2)* | 354.9 (50.3)* | 0.16 (0.03)* | 0.27 (0.04) |
| | Individual response | □■□□□□□ | ■■■■■■■ | ■■■■■■■ | ■■■■■■■ | □□□□□□□ | □□□■■■□ |
| CG | PRE | 0.099 (0.01) | 0.73 (0.05) | 412.9 (36.3) | 346.2 (54.9) | 0.21 (0.07) | 0.29 (0.04) |
| | POST | 0.100 (0.01) | 0.72 (0.04) | 409.3 (36.6) | 327.8 (63.2) | 0.22 (0.07) | 0.30 (0.04) |
| | Individual response | □■□■□■■■ | □□□□□□■□ | ■□□□■□□□ | □■□□■□□□ | □□■□■□□■ | ■■■■□□■■ |

**Figure 2** — Intragroup differences for the most representative variables of running kinematics investigated. Late swing APT: mean APT across 80% to 95% stride. Data are expressed as mean (SD). Gray tones indicate ES values greater than 0.8. Individual responses should be interpreted as absolute increase/decrease (black and gray, respectively). APT indicates anterior pelvic tilt; CG, control group; DBK, distance between knees; ES, effect size; IG, intervention group; MKVD, maximal knee vertical displacement; MVP, maximal vertical projection; TD, touchdown; TO, toe-off. *$P < .05$. **$P < .01$.

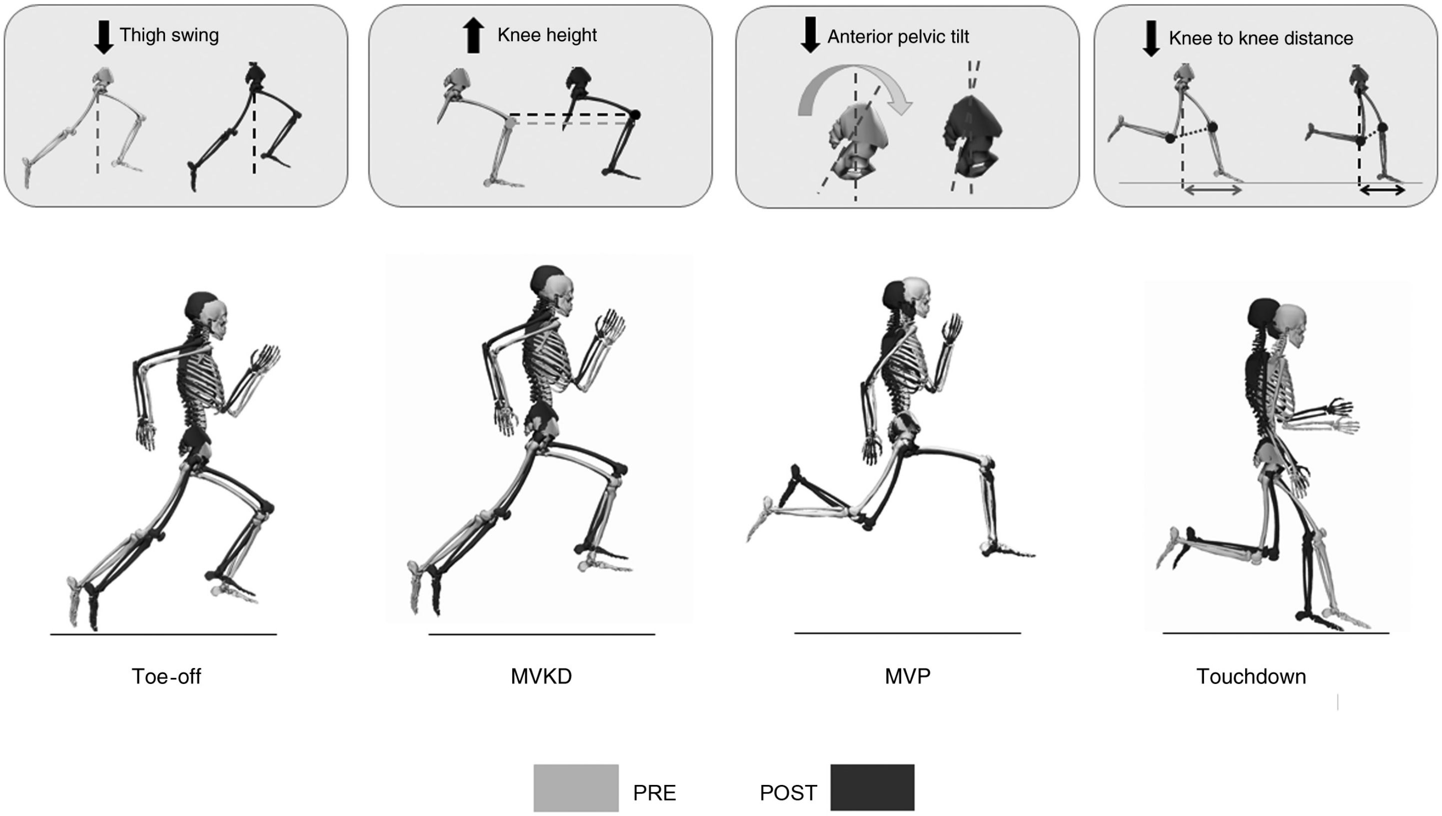

**Figure 3** — Visual representation of the identified changes between PRE and POST for the intervention group. MKVD indicates maximal knee vertical displacement; MVP, maximal vertical projection.

reached by the knee, followed by an increase in the thigh angular retraction velocity, as well as a decrease in the DBK at initial contact, along with a shorter landing distance and contact time. Finally, all these modifications were followed by a change in sprint performance, reflected in the significant decrease in the 0- to 5-, 5- to 10-, 10- to 15-, and 25- to 35-m split times and 0- to 20-m and 0- to 35-m cumulative split times recorded during the maximum sprint test, compared with CG during the same period of time.

This study is, to our knowledge, the first showing a change in pelvic kinematics after a multicomponent training intervention specifically directed to correct and decrease APT at maximum running speed.

## Interest of the Present Findings for HSI Risk Management

One of the reasons why the prevalence of BF injury could be higher would be related, among other factors, to a greater nonuniform elongation peak of the proximal BF during the late swing phase of maximal speed sprinting.[10] Assuming strain as the major determinant of tissue failure and considering that the ipsilateral elongation peak of the BF coincides with contralateral iliacus maximum stretch and the second peak pelvis anterior tilt all together during the late swing phase,[20,21] it seems logical to expect that a posterior tilt of the pelvis, as found in this study, would reduce the suggested BF musculotendon stretch and eccentric demand, probably specifically at its proximal region. The possible association between the pelvic joint movements and the BF behavior could have an anatomical origin since this muscle is the only hamstring muscle anatomically linked to ischial tuberosity with connections to the sacrotuberous ligament[22] structure, whose role has been proven as fundamental in the stabilization of the pelvis.[23]

The balance between the musculature functionally favoring APT iliopsoas, erector spinae, and the musculature counteracting it, such as the abdominals and gluteus during swing phase of HSR, seems to play a key role on BF strain and may explain the association found with HSI in prospective studies.[21,24]

However, given the intervention design of this study, it is impossible to know whether the decrease in APT is caused by the multimodal training intervention or is a consequence of the process of the individual's ability to acquire the desired sprint motor skills as a function of the practice related to the sprint technique program. It cannot be ruled out that certain parts of the program have advantageous and additive reciprocal effects, as it stands to reason that sprinting ability cannot be improved without a good underlying training and performance structure. In summary, a combined intervention of lumbopelvic control exercises mixed with a running technique program induced lower APT and can be considered one more tool within a multifactorial rehabilitation or prevention approach, especially in those athletes who show excessive APT and may be more susceptible to HSI.

## Lower-Limb Kinematics and Performance Relationship

Based on the reported results, it seems justified to assume that the observed lower-limb kinematic changes would place the IG

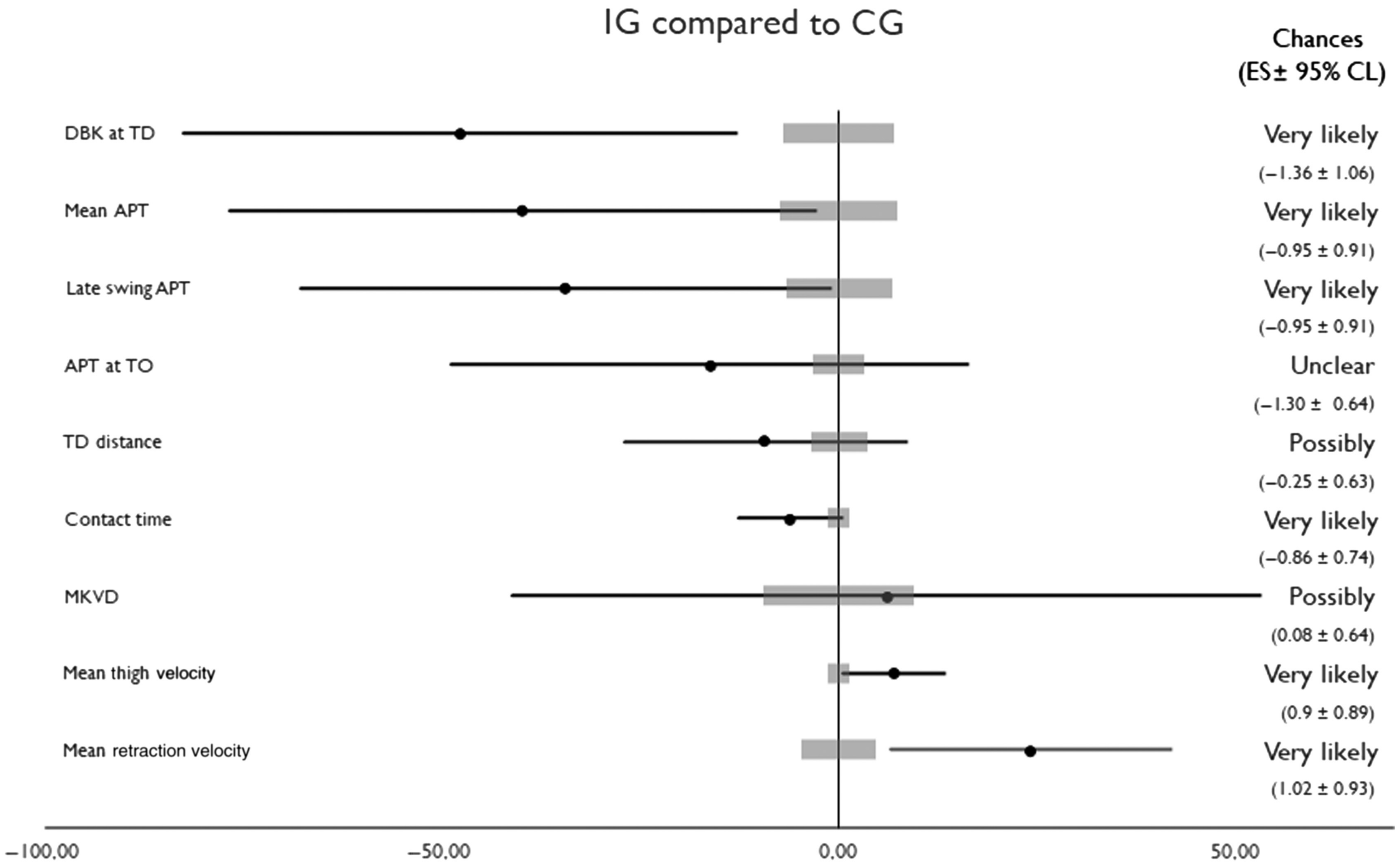

**Figure 4** — Efficiency of the multimodal program on the IG compared with CG over the most relevant kinematic variables investigated (bars indicate uncertainty in the true mean changes with 95% confidence intervals). Trivial areas were calculated from the smallest worthwhile change. Late swing APT: Mean APT across 80% to 95% stride. APT indicates anterior pelvic tilt; CL, confidence limit; CG, control group; DBK, distance between knees; ES, effect size; IG, intervention group; MKVD, maximal knee vertical displacement; TD, touchdown; TO, toe-off.

**Table 1 Changes in Sprint Performance Between PRE and POST**

| | CG | | | | IG | | | |
|---|---|---|---|---|---|---|---|---|
| **Sprint performance** | **PRE** | **POST** | **Δ% (±SD)** | **ES ± 95% CL** | **PRE** | **POST** | **Δ% (±SD)** | **ES ± 95% CL** |
| T0–5, s | 1.22 (0.09) | 1.21 (0.08) | −1.29 (7.02) | −0.24 ± 0.51 | 1.22 (0.07) | 1.14 (0.07)* | −6.97 (6.56) | −1.36 ± 0.16 |
| T5–10, s | 0.78 (0.03) | 0.77 (0.03)* | −1.34 (1.91) | −0.66 ± 0.56 | 0.81 (0.03) | 0.78 (0.03)* | −4.20 (3.08) | −1.57 ± 0.16 |
| T10–15, s | 0.69 (0.03) | 0.69 (0.03) | −0.68 (2.21) | −0.37 ± 0.51 | 0.7 (0.03) | 0.68 (0.02)* | −2.67 (4.08) | −1.32 ± 0.00 |
| T15–20, s | 0.64 (0.03) | 0.66 (0.03) | 2.61 (2.96) | 0.38 ± 0.49 | 0.65 (0.03) | 0.66 (0.03) | 1.55 (3.03) | 0.24 ± 0.99 |
| T20–25, s | 0.63 (0.04) | 0.63 (0.03) | −0.11 (1.88) | −0.04 ± 0.48 | 0.64 (0.03) | 0.64 (0.03) | 0.58 (5.96) | 0.56 ± 0.57 |
| T25–35, s | 1.23 (0.06) | 1.24 (0.06) | 0.85 (2.54) | 0.50 ± 0.52 | 1.27 (0.06) | 1.25 (0.07)* | −1.68 (2.05) | −1.34 ± 0.14 |
| T0–10, s | 1.99 (0.11) | 1.97 (0.11) | −0.01(0.04) | −0.27 ± 0.71 | 2.03 (0.06) | 1.92 (0.05)* | −5.31(0.04) | −1.38 ± 1.06 |
| T0–20, s | 3.32 (0.14) | 3.31 (0.15) | −0.01 (0.03) | −0.12 ± 0.70 | 3.38 (0.03) | 3.26 (0.03)** | −3.43 (0.02) | −1.50 ± 1.11 |
| T0–35, s | 5.17 (0.22) | 5.17 (0.24) | 0.01 (0.02) | 0.69 ± 0.69 | 5.29 (0.08) | 5.16 (0.16)* | −2.48 (0.02) | −1.08 ± 0.95 |
| Top speed | 8.91 (0.46) | 8.84 (0.55) | −0.90 (2.81) | −0.28 ± 0.71 | 8.49 (0.46) | 8.93 (0.53) | 4.75 (4.96) | 0.89 ± 0.89 |

Abbreviations: CG, control group; ES, effect size; IG, intervention group; CL, confidence limits.
Intragroup significant differences from PRE to POST training. *$P < .05$, **$P < .01$.

somewhere close to the targeted front-side mechanics technical model that is theoretically associated with better maximal speed sprint performance according to the literature.[13–15]

Interestingly and in contrast to the significant decrease in the sagittal plane of the pelvis motion shown in the late swing phase (Figures 1 and 3), we observed a significant overall increase in the frontal plane motion during the early swing phase (Figure 1) of maximal running speed. It has been suggested that a greater pelvis obliquity during push-off[25] as observed in the present study is associated with greater vertical GRF, which is a key determinant factor to reach and maintain high running speed.[25,26] Although GRFs were not recorded in this study, the changes recorded in the IG group could explain the performance improvement observed on the basis of the kinematic–kinetic relationship described in the literature. The new segmental alignment is recognized by a reduced pelvic anteversion throughout the stride (−5 deg for pelvic tilt along the stride) and a faster and more active recovery of the ipsilateral leg. A more upright position combined with a modified free leg offset shifts the back- to front-side mechanics in this new arrangement. As sprinting entails a sequence of segment positions/movements during which each position/movement results from the previous one and, in turn, influences the following one, the achievement of a higher knee position (+0.09 m) offers athletes a greater potential to accelerate the leg toward the ground (leg retraction) given the extended range of motion.[13–15] The enhanced impact-limb deceleration mechanism in the IG is supported by a significantly higher thigh angular retraction velocity (+17.5%), providing a biomechanical solution to “attack the ground” vertically and overcome the mechanical limitation of maximum sprinting speed imposed by the short stance duration requirement.[13–15,26] However, an active recovery of the trailing leg (scissorlike action) is required to achieve high vertical velocities on landing as part of the deceleration mechanism of the impact limb.[13] This ability is identified within the front-side mechanism model based on DBK at touchdown and is considered an indicator of “leg switch efficiency.”[13] According to our results, the IG presented a significantly decreased distance at this point (43% closer on average). Concomitantly, the fact that IG showed a higher mean thigh angular velocity supports and validates the data provided by knee separation and confirms that, as recently demonstrated, more vigorous scissorlike action of the thighs (flexion–extension reversals) is necessary to improve sprint performance.[27]

Parallel to an improvement in “leg switch efficiency,” the IG showed significantly higher thigh angular retraction velocities, as well as shorter but not significant TDd (5%) and ground contact times (6%) (Figure 3), which could be related to an overall more efficient impact deceleration mechanism, resulting in a greater vertical GRF component. Recently, Clark et al[27] demonstrated that both mean thigh angular velocity and retraction velocity had a strong positive linear relationship with the vertical velocity of the lower limb at the instant of touchdown. This factor, coupled with rigid ground contact and rapid deceleration of the lower limb upon ground contact, appears to be decisive for the development of the specific vertical forces needed to support faster speeds.[14,15,27]

Translating the results of this study (approximately one-tenth of a second decrease on 0–20 m and 0–30 m) into practice and taking into account that a 30- to 50-cm difference (approximately 0.04–0.06 s over 20 m) is probably enough in order to be decisive in one-on-one duels in football indicate the suitability of this type of intervention on team sports settings.[28] In summary, all the training-induced kinematic changes observed within the IG collectively align with the different studies, suggesting that forces are generated proximally and must be effectively transmitted distally via stiff lower limbs during HSR.[29]

However, our results show that changes in maximal speed sprint kinematics are possible with training, but they do not clearly prove that these are directly related to the performance improvement observed. This association should be taken with caution since (1) studies advocating the front-side mechanics concept use mere cross-sectional kinematic comparisons between sprinters of different level of performance[13] and (2) other studies did not confirm this association.[30] The fact that the subjects of the present study were physically active and used to sprinting but not elite could bias this association: it cannot be ruled out that sprint training alone could have induced performance improvements. Finally, the study was performed only on males, and further research is necessary in order to ascertain whether similar changes are possible in female subjects.

## Practical Applications

A 6-week intervention program, designed with the goal to preserve an optimal state of the structures (lumbopelvic multimodal program) that would allow a correct execution of the field running technique program, showed a decrease in the APT during the late swing phase of sprinting (potentially decreasing hamstring strain) as well as lower-limb kinematic changes associated with performance improvement. Therefore, altering body posture during sprinting could be one more strategy to use, if indicated, in addition to those commonly used within a multifactorial and individualized hamstring prevention approach and performance enhancement.

## Conclusion

This study showed for the first time that a multimodal intervention combining lumbopelvic control exercises with a running technique program was able to modify the kinematics (pelvis and lower limbs) of maximal speed sprinting. These alterations may collectively be associated with reduced tissue strain (injury risk) of the hamstrings and were concomitant with significant sprint performance improvement.

### Acknowledgments

This study was made possible by technical support from the Department for Health, University of Bath. The authors are grateful to Andrea Astrella from Sports Biomechanical Engineering for his illustrations and Victor Cuadrado for his support. The authors would like to thank the participants of this study for their cooperation and effort.

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