International Journal of Sports Physiology and Performance, 2021, 16, 974-984
https://doi.org/10.1123/ijspp.2020-0423

Human Kinetics
ORIGINAL INVESTIGATION

Swing Phase Mechanics of Maximal Velocity Sprints—Does Isokinetic Lower-Limb Muscle Strength Matter?

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Purpose: Concentric hip and eccentric knee joint mechanics affect sprint performance. Although the biarticular hamstrings combine these capacities, empirical links between swing phase mechanics and corresponding isokinetic outcome parameters are deficient. This explorative study aimed (1) to explain the variance of sprint velocity, (2) to compare maximal sprints with isokinetic tests, (3) to associate swing phase mechanics with isokinetic parameters, and (4) to quantify the relation between knee and hip joint swing phase mechanics. ***Methods:*** A total of 22 sprinters (age = 22 y, height = 1.81 m, weight = 77 kg) performed sprints and eccentric knee flexor and concentric knee extensor tests. All exercises were captured by 10 (sprints) and 4 (isokinetics) cameras. Lower-limb muscle balance was assessed by the dynamic control ratio at the equilibrium point. ***Results:*** The sprint velocity (9.79 [0.49] m/s) was best predicted by the maximal knee extension velocity, hip mean power (both swing phase parameters), and isokinetic peak moment of concentric quadriceps exercise ($R^2 = 60\%$). The moment of the dynamic control ratio at the equilibrium point ($R^2 = 39\%$) was the isokinetic parameter with the highest predictive power itself. Knee and hip joint mechanics affected each other during sprinting. They were significantly associated with isokinetic parameters of eccentric hamstring tests, as well as moments and angles of the dynamic control ratio at the equilibrium point, but restrictedly with concentric quadriceps exercise. The maximal sprints imposed considerably higher loads than isokinetic tests (eg, 13-fold eccentric knee joint peak power). ***Conclusions:*** Fast sprinters demonstrated distinctive knee and hip mechanics in the late swing phase, as well as strong eccentric hamstrings, with a clear association to the musculoarticular requirements of the swing phase in sprinting. The transferability of isokinetic knee strength data to sprinting is limited inter alia due to different hip joint configurations. However, isokinetic tests quantify specific sprint-related muscular prerequisites and constitute a useful diagnostic tool due to their predicting value to sprint performance.

Keywords: dynamometry, joint power, muscle strength ratio, hamstring strain injury, screening tool, inverse dynamics

Running at maximal speed poses high neurophysiological and biomechanical demands on the athlete's body.[1,2] The optimization of speed is a training goal of many sports, for example, track and field, soccer, or American football.[3–5] A lot of research has been conducted on how to maximize sprint velocity.[1,6–8] In this context, an important role has been attributed to hamstring mechanics.[6,9,10] Within the last 5 years, a growing body of research investigated the late swing phase.[4,7,11] Within this movement phase, the hamstrings' major action occurs while the knee joint rapidly extends and the hip is still flexed.[2,12,13] Thus, their muscle–tendon units undergo an active lengthening while absorbing energy.[14,15] The amount of work and peak moment imposed on the hamstrings considerably increases with running speed,[9,13] which makes them prone to overload injuries.[2,11,14,15] It has been suggested that the synergy of hip and knee joint mechanics in the late swing phase is crucial for optimizing sprint performance.[2,4,7,9] However, the biomechanical interplay between hip and knee joint mechanics under maximal sprint velocity is still not sufficiently understood and is lacking empirical evidence.

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Strength tests have been used to elucidate the performance and injury aspect of maximal sprints.[5,12,16–18] Maximal sprint velocity was significantly associated with quadriceps strength at high movement speed[16,17] and hamstring's rate of torque development.[5] Increased injury risk has been assigned to athletes with strength deficits of the hip extensors[18] and hamstrings.[12,18] However, discrepancies of participants (elite sprinters, youth soccer players, and recreational athletes); testing procedures (isometric and isokinetic measurements, different contraction modes, and angular velocities); and running speeds (7.7–9.9 m/s) present challenges to drawing firm conclusions from the existing evidence.

It is well accepted that the transferability of isokinetic knee strength data to sprinting is limited by its monoarticular nature and considerably lower movement velocity compared with the functional movement (900°/s–1200°/s).[6,12,16,17] However, it has been suggested that the equilibrium point of the eccentrically active hamstrings and the concentrically working quadriceps (dynamic control ratio at the equilibrium point [DCRe]) might be related to the swing phase mechanics of sprinting (Figure 1).[19,20] First, the magnitude of DCRe moments was similar to the peak eccentric knee flexor moments during the late swing phase of sprinting (1.8–2.5 N·m/kg).[9,10,21] Second, the DCRe angles corresponded to the knee joint angle at which the peak eccentric flexor moments were measured during sprinting (approximately 30°–40°).[4,13] Third, the hamstrings' peak moments in sprinting, as well as the DCRe moments, discriminated between the performance levels.[9,13,19]

To our knowledge, swing phase mechanics of maximal sprints have not yet been related to camera-based isokinetic strength tests

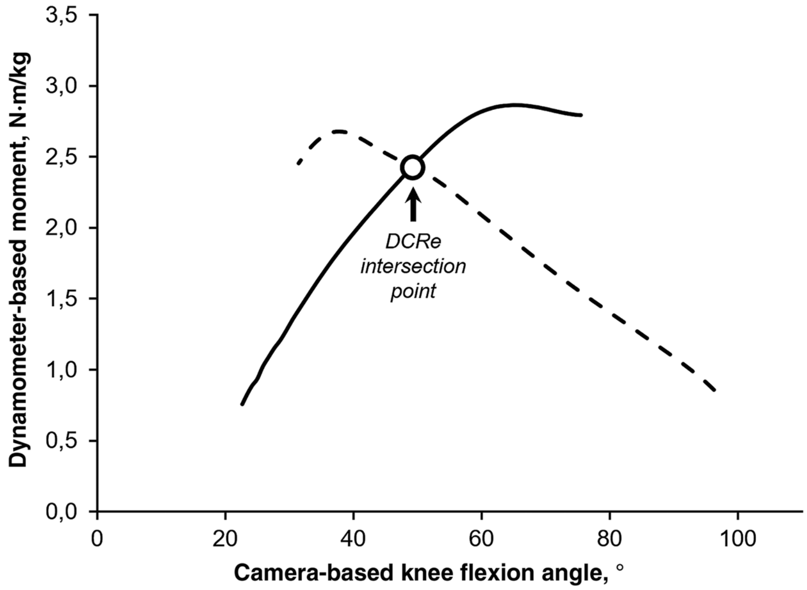

Figure 1 — Representative moment–knee flexion angle curves obtained from isokinetic concentric knee extensor (solid line) and eccentric knee flexor (dashed line) movements at 150°/s. The intersection point of both curves is called the "dynamic control ratio at the equilibrium point" (DCRe) and serves to assess the muscle balance between knee extensor and knee flexor muscles.

with extended hip joint. Thus, the aims of the present explorative study were

1. to explain the variance of sprint velocity by kinematic and kinetic measures of maximal sprints and isokinetic tests,
2. to compare the kinematics and kinetics of maximal sprints with those of isokinetic tests,
3. to associate swing phase mechanics with isokinetic parameters, and
4. to quantify the relation between knee and hip joint swing phase mechanics of sprints.

We hypothesized that

1. particular hip and knee joint kinematic and kinetic swing phase parameters of maximal sprints, together with isokinetic measures of lower-limb muscle balance, reveal significant associations to sprint velocity;
2. hip and knee joint kinematic and kinetic swing phase characteristics of maximal sprints significantly diverge from those of isokinetic lower-limb tests;
3. hip and knee joint kinematic and kinetic swing phase parameters of maximal sprints correspond to particular isokinetic test measures of knee extensor and knee flexor muscles; and
4. hip and knee joint kinematic and swing phase characteristics of maximal sprints demonstrate significant interactions.

Material and Methods

Participants

A total of 22 regional- to national-class male sprinters (mean [SD], age = 21.9 [2.2] y, height = 181.0 [7.0] cm, weight = 76.5 [7.7] kg) gave their written informed consent to voluntarily participate in the study. They differed in training history (range = 2–17 y), training volume (4–12 h/wk), and performance level (100-m personal record: 10.69–12.66 s). All of them were habituated to lower-extremity resistance training and isokinetic testing. All participants were free of lower-limb muscle and/or knee injuries within the last year. The local ethics commission at German Sport University, Cologne, confirmed that the requirements of the Declaration of Helsinki were met.

Instruments

Sprint Analysis. A sprint analysis was performed on an indoor synthetic running track by use of a 3-dimensional 10-camera (200 Hz) motion analysis system (VICON MX40; Vicon Motion Systems Ltd, Oxford, United Kingdom). The kinematic raw data were recorded within a calibrated volume of 800 × 200 × 200 cm (L × W × H) (Figure 2A). In order to create a lower-limb model consisting of 9 rigid segments, 28 spherical retroreflective markers (Ø = 8 mm) were attached bilaterally to the anterior and posterior superior iliac spines; greater trochanters; lateral and medial condyles of femurs; tibias; lateral and medial malleoli; heads of the first and fifth metatarsals; second proximal phalanges; and lateral, medial, and backside of the calcanei. The sprints were recorded and analyzed with VICON Nexus (version 2.3; Vicon Motion Systems Ltd, Oxford, United Kingdom).

Isokinetic Tests. All isokinetic tests were carried out via the active isokinetic dynamometer IsoMed 2000 (D & R Ferstl GmbH, Hemau, Germany). A double shin pad for unilateral knee flexion and extension was attached to the motor-driven axis of the device. The data were recorded by the manufacturer's computer software IsoMed Analyze (version 2.0; D&R Ferstl GmbH, Hemau, Germany) at 200 Hz. Four spherical retroreflective markers (Ø = 8 mm) remained per body side (acromion, trochanter major, lateral femoral

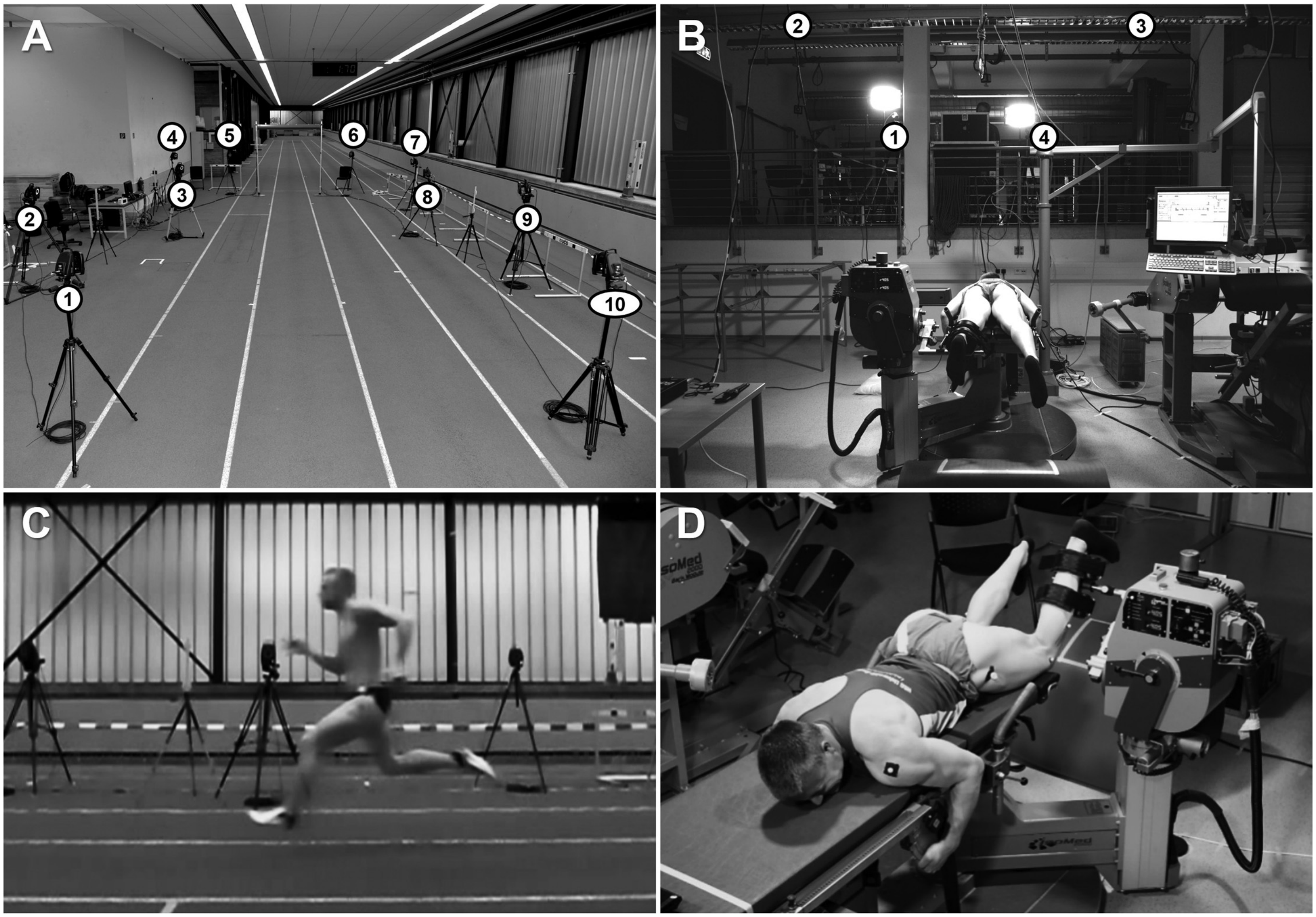

Figure 2 — An indoor synthetic running track (A) and an isokinetic laboratory (B) were equipped with motion capture systems consisting of 10 infrared and 4 high-speed video cameras. Kinetic and kinematic parameters obtained from maximal sprints (C) and isokinetic knee tests (D) were associated with sprint velocity and with each other.

epicondyle, and fibula head). The camera-based analysis of the isokinetic tests relied on 2 cameras per body side (acA640-120gc; Basler AG, Ahrensburg, Germany) at 100 fps (TEMPLO 8.2.358; Contemplas GmbH, Kempten, Germany), capturing the motion of the retroreflective markers in the calibrated measuring volume (L × W × H: 90 × 60 × 60 cm) (Figure 2B). The kinematic recording and analyses were performed with VICON Peak Motus (version 10.0.1; New York, NY).

Testing Procedure

Sprint Analysis. All tests were conducted on a single day. Each participant began with the sprints, followed by the isokinetic tests. Individual body dimensions and segmental inertial properties were determined by anthropometric measurements (body mass, body height, segment lengths, maximal and minimal segment circumferences). After an individual warm-up, all participants were asked to perform linear sprints with maximal velocity, which should be attained after an approach run of 30 to 40 m. Each sprinter ran 3 to 4 maximal sprints with his own spikes (Figure 2C).

Isokinetic Tests. After the sprints, isokinetic tests proceeded, with a rest of approximately 30 minutes. The tests followed a protocol with proven reliability.[22] In a preactivated muscular state, at 90° knee flexion (0° = full extension), the dynamometer axis was aligned with the participants' lateral femoral epicondyle, with the help of a laser pointer.[23] The distal part of the double shin pad was fixed by a strap approximately 2 to 3 cm proximal to the medial malleolus. After a static gravity correction measurement, the participants conducted an isokinetic warm-up consisting of 6 submaximal, discrete concentric, and eccentric repetitions (approximately 50%–80%) of the respective muscle group. The testing order was stratified such that the limbs were alternatingly tested.[22,24] For knee flexion (110°–0° knee joint's range of motion [ROM_{knee}]), the participants were asked to lie prone (extended hip) by pushing their trunk with their hands to the lounger, promoting higher flexor moments compared with the seated and supine position (Figure 2D).[25] Knee extensions (0°–90° ROM_{knee}) were performed in the supine position (extended hip), with handgrips providing sufficient stability.

All tests were conducted in a single direction (discrete movements) at 150°/s because the DCRe parameters are most reliable at this angular velocity.[20] Each set consisted of 5 repetitions (2 submaximal and 3 with maximal effort). The last 3 repetitions were selected for further analysis. A 1-minute interset rest ensured sufficient recovery.[22] Strong verbal encouragement promoted maximum exertion.

Data Processing

Inverse Dynamic Model for Sprint Analysis. The kinematic raw data were filtered by a recursive fourth-order Butterworth low-pass filter at 40-Hz cutoff frequency. The Anybody Modeling System (AnyBody Technology A/S, Aalborg, Denmark) was used to perform lower-limb inverse dynamics, according to the anatomical landmark scaled model of Lund et al.[26] Standing reference trials were recorded for each subject to create a stick-figure model that was used to scale a cadaver data set into subject-specific joint parameters. The modeled head and trunk were driven by the pelvis markers. To calculate inertial properties more accurately, the subject's whole-body anthropometrics were measured to adjust the inverse dynamic model. The distribution of body mass was accomplished according to Hanavan.[27] The foot and shoe were considered one segment. Kinematic and kinetic variables were time normalized to the swing phase. A total of 179 eccentric phases of knee extensions and 234 knee joint peak moments during the swing phase were used for further analyses. Further data processing was conducted with custom-built MatLab routines (R2013b; The MathWorks, Natick, MA). Peak moments of inertia and corresponding data were extracted from the entire swing phase in the sagittal plane. The swing phase was determined as the time between the takeoff of one leg and the touchdown of the same leg, identified by the vertical displacement of the toe markers. Joint moments are presented as external moments normalized to each subject's mass. Sprint velocity was calculated for each step as the mean horizontal velocity of the center of mass after takeoff of the respective foot. It was then averaged across trials and participants. Joint power during sprinting was determined as the product of actual joint angular velocity and its corresponding moment value at that time.

Analysis of Isokinetic Tests. The raw data (200 Hz) were recorded by the manufacturer's software (IsoMed analyze [version 2.0]) and stored as ASCII files. A custom-made software (C++) isolated the isokinetic ROM (±1% deviation of angular velocity) and filtered the data (fifth-order Butterworth low-pass filter, 6-Hz cutoff frequency). For each testing condition, the trial with the highest gravity-corrected peak moment was selected. For each angular velocity, the DCRe with the highest moment out of 9 intersection points (each combination of the 3 flexor and extensor movements) was identified.[20,24] Peak power was calculated as product of actual camera-based angular velocity and moment value at the time of peak power.[23] Hip and knee flexion angles (0° = full extension) were calculated 3-dimensionally, and sagittal plane kinematics were taken for further analysis.[23,28]

Statistical Analysis

For all data, normal distribution and variance homogeneity were confirmed by the Kolmogorov–Smirnov ($P \leq .05$) and Levene test ($P \leq .10$). Dependent *t* tests examined the differences between the kinetic and kinematic parameters obtained from the sprinting and isokinetic tests. The effect sizes are indicated as Cohen *d* (≥0.8 large, 0.8–0.5 moderate, 0.5–0.2 small, <0.2 negligible), specifying the meaningfulness of the respective differences.[29] Stepwise regression analyses served to explain the variance of sprint velocity. Pearson correlation analyses determined the strength of the linear regressions between selected parameters. As recommended, *r* values of ≥.9 and <.3 were rated as very strong and negligible relations, respectively. The spans between 0.7 to 0.9, 0.5 to 0.7, and 0.3 to 0.5 were subsequently interpreted as strong, moderate, and weak relationships.[30] Accordingly, the corresponding R^2 values of 81%, 49%, 25%, and 9% were selected for classification. All statistical tests were calculated with SPSS (version 23.0; SPSS Inc, Chicago, IL). The level of significance was set at $P \leq .05$.

Results

The participants achieved an average sprint velocity of 9.79 (0.49) m/s. Sprint velocity was best predicted by a stepwise regression model involving maximal knee extension velocity, hip mean power of sprints, and isokinetic peak moment of concentric quadriceps exercise ($R^2 = 60\%$; Table 1). The maximal sprints revealed significantly higher peak knee flexor moments (Figure 3A), knee extension velocities, ROM_{knee}, hip flexion angles (Figure 3B), and peak and mean knee joint power than isokinetic exercise (Table 4). The knee flexion angles at the peak knee flexor moment reached similar values as the DCRe angles. The DCRe moment ($R^2 = 39\%$) was the isokinetic parameter with the highest predictive power of sprint velocity itself (Table 2). All kinetic parameters of eccentric hamstring

Table 1 Identification of Parameters Obtained From Sprint Analysis and Isokinetic Knee Tests to Explain the Interindividual Differences of Sprint Velocity via Stepwise Regression ($P \leq .05$)

Input variable	Parameter 1	P	R^2	Parameter 2	P	Adjusted R^2	Parameter 3	P	Adjusted R^2
Sprint and isokinetic parameters (Tables 2 and 3)	ω_{max}knee	.001	43.7%	P_{mean}hip	.029	51.9%	PM_{Qcon}	.044	59.7%
Hip and knee mechanics (Tables 2 and 3)	ω_{max}knee	.001	43.7%	P_{mean}hip	.029	51.9%			
Sprint and isokinetic parameters (Tables 2 and 3)	ω_{max}knee	.001	43.7%	DCRe moment	.038	50.7%			
Hip and knee kinematics (Table 3)	ω_{max}knee	.001	43.7%	ω_{max}hip	.271				
Hip and knee kinetics (Table 2)	P_{mean}hip	.001	42.8%	PM_{hip}	.223				
Isokinetic strength parameters (Table 2)	DCRe moment	.002	38.6%	PM_{Qcon}	.132				
Isokinetic angular parameters (Table 3)	φ_{KF} P_{max}Hecc	.045	18.7%	APM_{Hecc}	.300				

Abbreviations: APM, angle of peak moment; DCRe, dynamic control ratio at the equilibrium point; Hecc, eccentric hamstring; PM, peak moment; P_{max}, peak power; P_{mean}, mean power; Qcon, concentric quadriceps; φ_{KF}, knee flexion angle; ω_{max}, maximal joint angular velocity.

Table 2 Regression Analyses of Kinetic Parameters Obtained From Maximal Sprints and Isokinetic Knee Tests

	Sprint mechanics								
		PM, N·m/kg		CW, J/kg		P_{max}, W/kg		P_{mean}, W/kg	
	v, m/s	Knee (ecc)	Hip (con)	Knee (ecc)	Hip (con)	Knee (ecc)	Hip (con)	Knee (ecc)	Hip (con)
v, m/s		**P = .019 r = .494 R^2 = 24.4%**	P = .433 r = .176	**P = .003 r = .602 R^2 = 36.2%**	**P = .040 r = .442 R^2 = 19.5%**	**P = .003 r = .602 R^2 = 36.2%**	**P = .044 r = .434 R^2 = 18.8%**	**P = .036 r = .449 R^2 = 20.2%**	**P = .001 r = .654 R^2 = 42.8%**
Isokinetics									
Hecc									
PM, N·m/kg	**P = .008 r = .551 R^2 = 30.4%**	**P = .014 r = .517 R^2 = 26.7%**	P = .463 r = .165	**P = .048 r = .426 R^2 = 18.1%**	P = .077 r = .385	**P = .001 r = .666 R^2 = 44.4%**	P = .121 r = .340	P = .226 r = .269	**P = .003 r = .602 R^2 = 36.2%**
CW, J/kg	**P = .004 r = .595 R^2 = 35.4%**	**P = .017 r = .501 R^2 = 25.1%**	P = .337 r = .215	**P = .011 r = .534 R^2 = 28.5%**	**P = .010 r = .535 R^2 = 28.6%**	**P = .007 r = .555 R^2 = 30.8%**	**P = .045 r = .431 R^2 = 18.6%**	P = .075 r = .387	**P = .004 r = .592 R^2 = 35.0%**
P_{max}, W/kg	**P = .009 r = .544 R^2 = 29.6%**	**P = .029 r = .465 R^2 = 21.6%**	P = .405 r = .187	P = .064 r = .401	P = .055 r = .415	**P = .016 r = .508 R^2 = 25.8%**	P = .172 r = .302	P = .249 r = .257	**P = .019 r = .496 R^2 = 24.6%**
P_{mean}, W/kg	**P = .003 r = .597 R^2 = 35.6%**	**P = .017 r = .503 R^2 = 25.3%**	P = .318 r = .223	**P = .010 r = .537 R^2 = 28.8%**	**P = .011 r = .530 R^2 = 28.1%**	**P = .007 r = .554 R^2 = 30.7%**	**P = .042 r = .437 R^2 = 19.1%**	P = .071 r = .393	**P = .003 r = .599 R^2 = 35.9%**
DCRe moment, N·m/kg	**P = .002 r = .622 R^2 = 38.7%**	**P = .014 r = .518 R^2 = 26.8%**	P = .782 r = .063	P = .066 r = .399	P = .102 r = .358	**P = .002 r = .631 R^2 = 39.8%**	P = .224 r = .270	P = .271 r = .245	**P = .008 r = .548 R^2 = 30.0%**
Qcon									
PM, N·m/kg	**P = .008 r = .548 R^2 = 30.0%**	P = .355 r = .207	P = .722 r = .081	P = .975 r = .007	P = .613 r = −.114	P = .076 r = .386	P = .705 r = −.085	P = .642 r = .105	P = .293 r = .235
CW, J/kg	P = .384 r = .195	P = .782 r = −.062	P = .730 r = .078	P = .900 r = −.029	P = .696 r = −.088	P = .828 r = −.049	P = .185 r = −.293	P = .856 r = .041	P = .912 r = −.025
P_{max}, W/kg	P = .991 r = −.002	P = .478 r = −.159	P = .685 r = .092	P = .231 r = −.266	P = .164 r = −.308	P = .477 r = −.160	P = .197 r = −.286	P = .418 r = −.182	P = .374 r = −.199
P_{mean}, W/kg	P = .332 r = .217	P = .780 r = −.063	P = .728 r = .079	P = .944 r = −.016	P = .709 r = −.084	P = .858 r = −.040	P = .203 r = −.283	P = .896 r = −.030	P = .953 r = −.013

Abbreviations: con, concentric; CW, contractional work; DCRe, dynamic control ratio at the equilibrium point; ecc, eccentric; Hecc, eccentric hamstring; PM, peak moment; P_{max}, peak power; P_{mean}, mean power; Qcon, concentric quadriceps; *v*, sprint velocity. Note: Significant relationships ($P \leq .05$) between respective parameters are highlighted in bold and by indicating the corresponding coefficients of determination (R^2).

Table 3 Regression Analyses of Kinematic Parameters Obtained From Maximal Sprints and Isokinetic Knee Tests

	Sprint mechanics								
		φKFPM, °		$\varphi_{KF}P_{max}$, °		ω_{max}, °/s		ω_{mean}, °/s	
	v, m/s	Knee	Hip	Knee	Hip	Knee	Hip	Knee	Hip
v, m/s		**P = .021 r = −.488 R^2 = 23.8%**	P = .626 r = .110	**P = .021 r = −.488 R^2 = 23.8%**	P = .532 r = −.141	**P = .001 r = .661 R^2 = 43.7%**	P = .252 r = .255	P = .483 r = .158	P = .231 r = .266
Isokinetics									
Hecc									
APM_{KF}, °	P = .553 r = −.134	P = .828 r = .049	P = .215 r = −.275	P = .377 r = .198	P = .809 r = .055	P = .857 r = .041	P = .346 r = −.211	P = .661 r = −.099	P = .137 r = −.327
$\varphi_{KF}P_{max}$, °	**P = .045 r = −.432 R^2 = 18.7%**	P = .400 r = .189	P = .770 r = −.066	P = .457 r = .167	P = .509 r = −.149	P = .647 r = −.104	P = .413 r = −.184	P = .349 r = −.210	P = .180 r = −.296
DCRe angle, °	P = .673 r = −.095	**P = .027 r = −.471 R^2 = 22.2%**	P = .098 r = −.362	**P = .025 r = −.475 R^2 = 22.6%**	**P = .031 r = −.459 R^2 = 21.1%**	**P = .027 r = .470 R^2 = 22.1%**	**P = .005 r = .572 R^2 = 32.7%**	P = .643 r = .105	P = .091 r = .369
Qcon									
APM_{KF}, °	P = .168 r = −.305	P = .222 r = .271	**P = .031 r = −.461 R^2 = 21.3%**	P = .118 r = .343	P = .978 r = .006	P = .583 r = −.124	P = .285 r = −.239	P = .863 r = .039	P = .421 r = −.181
$\varphi_{KF}P_{max}$, °	P = .207 r = −.280	P = .589 r = .122	P = .189 r = −.291	P = .366 r = .202	P = .403 r = −.188	P = .941 r = −.017	P = .612 r = −.114	P = .669 r = .096	P = .413 r = −.184

Abbreviations: APM, angle of peak moment; DCRe, dynamic control ratio at the equilibrium point; Hecc, eccentric hamstring; PM, peak moment; P_{max}, peak power; Qcon, concentric quadriceps; *v*, sprint velocity; φ_{KF}, knee flexion angle; ω_{max}, maximal joint angular velocity; ω_{mean}, mean joint angular velocity. Note: Significant relationships ($P \leq .05$) between respective parameters are highlighted in bold and by indicating the corresponding coefficients of determination (R^2).

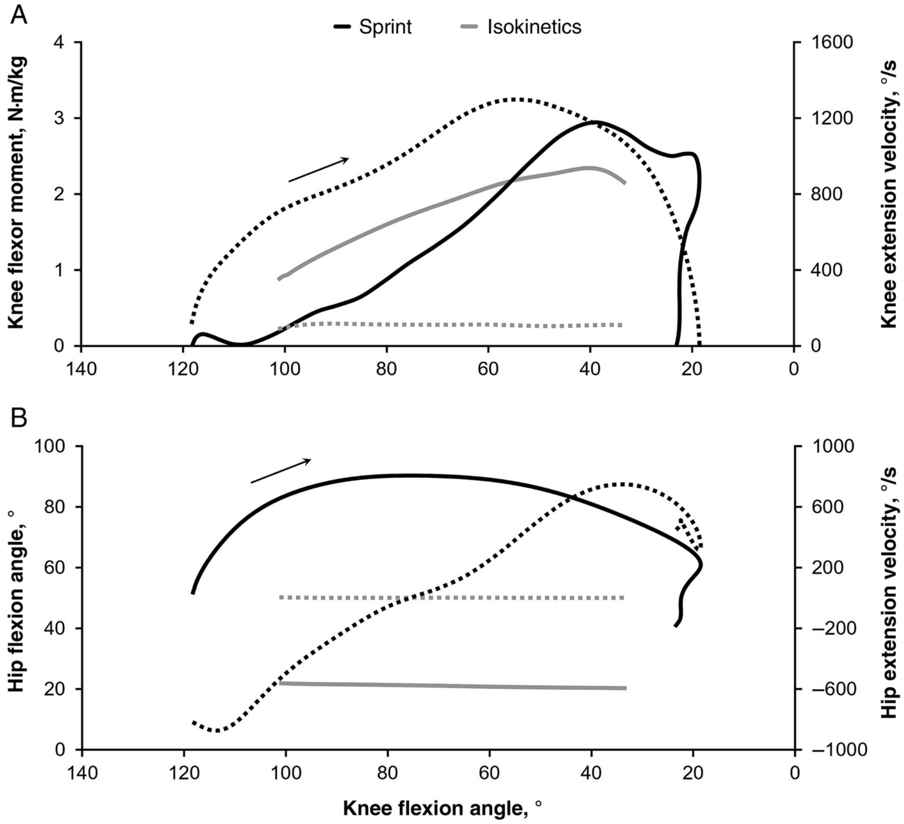

Figure 3 — Representative knee (A) and hip (B) mechanics of maximal sprints (black lines) and isokinetic eccentric knee flexor tests (gray lines). The arrows indicate the direction of chronological sequence. Eccentric knee flexor moments (solid lines in A) and knee extension velocities (dashed lines in A), as well as knee range of motion of isokinetic tests, were lower compared with maximal sprints, whereas peak moments emerged at similar knee flexion angles (approximately 40°). Hip flexion angles (solid lines in B) and hip extension velocities (dashed lines in B) considerably differed in shape and magnitude between sprints and isokinetics.

Table 4 Comparison of Selected Parameters (Mean [SD]) Obtained From Inverse Dynamic Swing Phase Analyses of Maximal Sprints and Camera-Based Isokinetic Strength Tests

	Peak knee flexor moment or DCRe moment, N·m/kg	Knee flexion angle at peak knee flexor moment or DCRe angle, °	Hip flexion angle at peak knee flexor moment or DCRe moment, °	Associated knee angular velocity, °/s	Minimal knee flexion angle, °	Maximal knee flexion angle, °	Eccentric knee joint peak power, W/kg	Eccentric knee joint mean power, W/kg
Sprinting	2.62 (0.30)	40.5 (6.0)	73.4 (7.7)	999.4 (137.)3	19.7 (6.6)	118.3 (4.5)	51.2 (9.6)	17.1 (2.3)
Isokinetics	2.00 (0.28)	40.8 (5.7)	12.5 (5.1)	103.7 (7.3)	29.9 (4.3)	97.3 (4.4)	3.9 (0.6)	3.1 (0.4)
P	**<.001**	.889	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**
d	**2.19**	0.05	**9.54**	**9.43**	**1.87**	**4.85**	**7.12**	**8.68**

Abbreviation: DCRe, dynamic control ratio at the equilibrium point. Note: Significant differences ($P \leq .05$) between both conditions are highlighted in bold.

exercise were related to sprint velocity ($R^2 \leq 36\%$), as well as to knee ($R^2 \leq 44\%$) and hip kinetics ($R^2 \leq 36\%$), during the late swing phase. In contrast, only peak moments of concentric quadriceps tests were significantly associated with sprint velocity ($R^2 = 30\%$). The DCRe angles were weakly related to knee and hip kinematics ($R^2 \leq 33\%$), whereas other kinematic parameters revealed negligible links to sprinting (Table 3). The knee and hip joint significantly affected each other during the swing phase of maximal sprints (Table 5). Contractional work, peak, and mean power demonstrated strong interrelations ($R^2 \leq 76\%$).

Discussion

This exploratory study aimed (1) to explain the variance of sprint velocity by kinematic and kinetic measures of maximal sprints and isokinetic tests, (2) to compare the kinematics and kinetics of maximal

Table 5 Regression Analyses of Concentric Hip and Eccentric Knee Mechanics Parameters Obtained During the Late Swing Phase of Maximal Sprints

		Eccentric knee mechanics					
	v, m/s	PM, N·m/kg	CW, J/kg	P_{max}, W/kg	P_{mean}, W/kg	ω_{max}, °/s	ω_{mean}, °/s
v, m/s		**$P=.019$ $r=.494$ $R^2=24.4\%$**	**$P=.003$ $r=.602$ $R^2=36.2\%$**	**$P=.003$ $r=.602$ $R^2=36.2\%$**	**$P=.036$ $r=.449$ $R^2=20.2\%$**	**$P=.017$ $r=.504$ $R^2=25.4\%$**	$P=.483$ $r=.158$
Concentric hip mechanics							
PM, N·m/kg	$P=.433$ $r=.176$	$P=.227$ $r=.268$	$P=.068$ $r=.396$	$P=.378$ $r=.198$	**$P=.015$ $r=.513$ $R^2=26.3\%$**	$P=.819$ $r=.052$	$P=.234$ $r=.265$
CW, J/kg	**$P=.040$ $r=.442$ $R^2=19.5\%$**	**$P<.001$ $r=.698$ $R^2=48.7\%$**	**$P<.001$ $r=.795$ $R^2=63.2\%$**	**$P=.001$ $r=.647$ $R^2=41.9\%$**	**$P<.001$ $r=.734$ $R^2=53.9\%$**	$P=.069$ $r=.395$	$P=.982$ $r=.005$
P_{max}, W/kg	**$P=.044$ $r=.434$ $R^2=18.8\%$**	**$P<.001$ $r=.727$ $R^2=52.9\%$**	**$P<.001$ $r=.810$ $R^2=65.6\%$**	**$P=.003$ $r=.609$ $R^2=37.1\%$**	**$P<.001$ $r=.763$ $R^2=58.2\%$**	$P=.238$ $r=.262$	$P=.357$ $r=.206$
P_{mean}, W/kg	**$P=.001$ $r=.654$ $R^2=42.8\%$**	**$P<.001$ $r=.757$ $R^2=57.3\%$**	**$P<.001$ $r=.872$ $R^2=76.0\%$**	**$P<.001$ $r=.766$ $R^2=58.7\%$**	**$P<.001$ $r=.807$ $R^2=65.1\%$**	**$P=.022$ $r=.486$ $R^2=23.6\%$**	$P=.235$ $r=.264$
ω_{max}, °/s	$P=.252$ $r=.255$	$P=.805$ $r=-.056$	$P=.174$ $r=.301$	$P=.345$ $r=.211$	$P=.355$ $r=.207$	**$P=.002$ $r=.621$ $R^2=38.6\%$**	**$P=.012$ $r=.526$ $R^2=27.7\%$**
ω_{mean}, °/s	$P=.231$ $r=.266$	$P=.620$ $r=.112$	$P=.072$ $r=.391$	$P=.126$ $r=.336$	**$P=.018$ $r=.500$ $R^2=25.0\%$**	**$P=.001$ $r=.639$ $R^2=40.8\%$**	**$P=.003$ $r=.603$ $R^2=36.4\%$**

Abbreviations: CW, contractional work; Hecc, eccentric hamstring; PM, peak moment; P_{max}, peak power; P_{mean}, mean power; Qcon, concentric quadriceps; v, sprint velocity; ω_{max}, maximal joint angular velocity; ω_{mean}, mean joint angular velocity. Note: Significant relationships ($P \le .05$) between respective parameters are highlighted in bold and by indicating the corresponding coefficients of determination (R^2).

sprints with those of isokinetic tests, (3) to associate swing phase mechanics with isokinetic parameters, and (4) to quantify the relation between knee and hip joint swing phase mechanics of sprints. The following discussion is divided according to these 4 hypotheses:

1. Particular hip and knee joint kinematic and kinetic swing phase parameters of maximal sprints, together with isokinetic measures of lower-limb muscle balance, reveal significant associations to sprint velocity;
2. Hip and knee joint kinematic and kinetic swing phase characteristics of maximal sprints significantly diverge from those of isokinetic lower-limb tests;
3. Hip and knee joint kinematic and kinetic swing phase parameters of maximal sprints correspond to particular isokinetic test measures of knee extensor and knee flexor muscles; and
4. Hip and knee joint kinematic and swing phase characteristics of maximal sprints demonstrate significant interactions.

Explaining the Variance of Sprint Velocity by Kinematic and Kinetic Measures of Maximal Sprints and Isokinetic Tests

The present results showed that sprint velocity was best predicted by maximal knee extension velocity, hip mean power of sprints, and isokinetic peak moment of concentric quadriceps exercise ($R^2=60\%$; Table 1). This is in accordance with recent literature, highlighting the powerful "pawing action" of the lower limb in the late swing phase.[3,6,7] Previous studies revealed that peak moments of fast concentric knee extensions ($R^2=50\%$ at 230°/s[16] and $R^2=43\%$ at 240°/s[17]) were the best predictors of sprint performance. In the present sample, peak moments of concentric quadriceps tests were significantly associated with sprint velocity, but to a lesser extent ($R^2=30\%$). Whether this is attributable to the lower angular velocity (150°/s) used in this study or to other methodological differences (eg, determination of sprint velocity) remains a matter of debate.

All analyzed parameters of eccentric hamstring exercise were significantly related to the sprint velocity of sprinters ($R^2 \le 36\%$). These still weak correlations confirmed previous findings with soccer players and a heterogenous sample.[5,17] However, other studies failed to prove correlations between hamstring strength parameters and sprint velocity due to methodological constraints (eg, submaximal sprints, seated isokinetic tests).[6,16] The DCRe moment ($R^2=39\%$) was the isokinetic parameter with the highest predictive power of sprint velocity itself (Table 2). This parameter represents the intersection point in the moment-knee flexion angle curves, where the eccentrically active hamstrings are able to fully brake the extension moment produced by the concentrically contracting quadriceps.[19,20,24] Peak moments and negative work imposed on the hamstrings' muscle–tendon unit prior to foot strike increased with running speed,[9,13] indicating that faster athletes need increased muscular capacities to produce and tolerate these loads without suffering from an overload injury.[2,11,14,15] This specific capacity is reflected by DCRe moments.

Schache et al[9] found very strong relations ($R^2 \ge 87\%$) of sprint velocity to hip and knee joint work during the late swing phase. Although the range of the analyzed velocities was much wider compared with those in the present study (3.5–9.9 vs 8.8–10.5 m/s), these results emphasized that parameters representing entire swing phase sections (eg, work, mean power) rather than peak values are performance limiting in sprinting.[9,10,21] Within the relatively narrow range of sprint velocities, this fact cannot be confirmed for either the knee and hip swing phase mechanics or the measures of isokinetic hamstring exercise (Table 2).

Kinematics and Kinetics of Maximal Sprints Versus Isokinetic Tests

As hypothesized, maximal sprints imposed considerably higher loads (eg, 13-fold eccentric knee joint peak power) on the athlete's body compared with isokinetic exercise (Table 4). As previously published, the peak knee flexor moments were 31% higher in sprinting.[11] Due to its biarticular movement, maximal sprints evoked knee extension velocities of nearly 10-fold values compared with isokinetic tests. Within the fast hip extension during the late swing phase, the shank acts as an inertial pendulum because the knee extensor muscles are not activated.[13] Besides, ROM_{knee} and hip flexion angles significantly diverged (Figure 3A and 3B). However, knee flexion angles at the peak knee flexor moment reached similar values to the DCRe angles (Table 4).

Peak knee flexor moments in sprinting (2.2–3.3 N·m/kg) were higher than previously reported (1.8–2.5 N·m/kg)[9,10,21] (Table 4). These high values correspond to the findings of Sun et al.[11] Deviations might be explained by different body models used and by the mean sprint velocity of the present study, which was on the published work's top end (9.8 vs 7.7–9.9 m/s). Eccentric peak flexor moments are significantly higher when hip flexion is higher because the fascicle length of the biarticular hamstrings is more sensitive to hip flexion than to knee extension.[2,4] Thus, it is reasonable that the knee flexor moments at DCRe emerging at 13° hip flexion were considerably lower compared with sprinting, where the peak knee flexor moments occurred at 73° hip flexion (Table 4). Thus, the present findings quantify the transferability of isokinetic knee strength data to sprinting.[6,12,16,17]

Association Between Swing Phase Mechanics and Isokinetic Parameters

To our knowledge, the relationship between swing phase mechanics and isokinetic parameters has not been investigated yet. All analyzed parameters of eccentric hamstring exercise were related to knee (PM, CW, and P_{max}) ($R^2 \leq 44\%$) and hip kinetics (CW, P_{max}, P_{mean}) ($R^2 \leq 36\%$) during the late swing phase, whereas concentric quadriceps exercise did not reveal any association (Table 2). The significant correlations were weak to moderate ($18\% \leq R^2 \leq 44\%$). Despite their limited predictive value, some interrelationships emphasized interesting links. Eccentric hamstring peak moments and isokinetic mean power were moderately related to the knee joint peak power (44% and 31%) and hip joint mean power (36% each) of maximal sprints (Table 2). This finding underlined the important biarticular role of the hamstrings, which can be estimated by prone isokinetic knee flexor tests.[2,15] However, a valid assessment of isokinetic power values can only be guaranteed by camera-based analyses.[23] This was the first study comparing camera-based power values of isokinetic tests with joint power during functional movements.

The DCRe moments revealed similar moderate relationships to the knee joint peak power (40%) and hip joint mean power (30%) of maximal sprints (Table 2). These numbers supported its predictive value to withstand high eccentric loads of the hamstring muscles,[19,20] which can be partially transferred to the late swing phase mechanics of maximal sprints. The DCRe angles were weakly related to knee ($21\% \leq R^2 \leq 22\%$) and hip kinematics ($21\% \leq R^2 \leq 33\%$), whereas other kinematic parameters revealed only negligible associations with sprinting (Table 3). In this context, special attention must be directed to the DCRe angles' positive correlations to maximal knee and hip extension velocities. They emphasize that fast and forceful knee extension can only be executed if the hamstrings' muscle–tendon unit is able to tolerate the imposed strain without getting injured.[13–15] In addition, improved lower-limb muscle balance—equal to higher DCRe angles—mirrors the athlete's ability to realize a powerful "pawing action" with an almost fully extended knee joint (Table 3).[6]

Interrelation of Knee and Hip Joint Mechanics During Late Swing Phase of Sprinting

Confirming the fourth hypothesis, contractional work, peak, and mean power of the concentrically working hip joint and the eccentrically active knee joint strongly affected each other ($R^2 \leq 76\%$) during the late swing phase of maximal sprints (Table 5). To our knowledge, this interdependence has not been investigated yet, although it has been frequently suggested.[2,4,7,9] The present findings emphasize that the knee extension within the late swing phase is initiated by a fast and forceful hip extension.[1,3,10] This hip extension is driven by the biarticularly working hamstrings, which are the major hip extensors when the hip is flexed.[2,15] The moderate correlations between peak and mean extension velocities of the knee and hip joint ($28\% \leq R^2 \leq 41\%$) underline this technical feature (Table 5). It is known that the lumbo-pelvic muscles influence hamstring stretch to a greater extent than the knee and ankle muscles actually do.[13] This interrelation suggests that multijoint instead of single-joint muscle balance scores might be suitable for sprint-related tests.[12,18] This knowledge is important for coaches, physiotherapists, and scientists to improve the synergy of knee and hip swing phase mechanics in sprinting to optimize sprint velocity.[3]

Practical Applications

During the late swing phase of maximal sprints, the knee extension is initiated by a fast and forceful hip extension driven by the biarticularly working hamstrings.[2,15] Thereby, the shank acts as an inertial pendulum, leading to a high eccentric loading of the hamstring muscles throughout the powerful "pawing action" of the lower limb in the late swing phase.[3,6,7,13] The present findings emphasize that contractional work, peak, and mean power of the concentrically working hip joint and the eccentrically active knee joint strongly affected each other ($R^2 \leq 76\%$). This knowledge is important for coaches, physiotherapists, and scientists to improve the synergy of knee and hip swing phase mechanics in sprinting in order to optimize maximal sprint velocity by purposive strength and conditioning, as well as by teaching distinctive neuromuscular activation patterns.[3,4]

The isokinetic measures were able to predict a big proportion of the variance of maximal sprint velocity within a relatively narrow performance range (8.8–10.5 m/s). In addition, they were significantly correlated to the knee and hip swing phase parameters. However, knee angular velocities emerging during the late swing phase of sprinting cannot be replicated at isokinetic dynamometers.[12] Even if viable, both mechanical (eg, valid velocity adjustment) and psycho-physiological reasons (eg, injury scare) would impair the validity of such data. Prospective isokinetic knee flexor strength tests should incorporate triangular pelvis pads, ensuring greater hip flexion. Although seated isokinetic tests with comparable hip flexion have been conducted,[6,12,18] Worrell et al[25] recommended knee flexor tests in the prone position. Significantly greater concentric and eccentric peak knee flexor moments can be achieved in the prone position due to a favorable modulation of flexor muscle tones (tonic labyrinthine reflex), owing to the head position. Consequently, seated hamstring tests should be avoided.[25]

The camera-based knee angular velocity substantially deviated from the default settings of the dynamometer (104°/s vs 150°/s, Table 4) due to a combined knee axis displacement and hip flexion.[23,28] Consequently, a broader use of camera-based analysis is recommended for isokinetic tests. Among other factors, soft tissue artifacts of skin markers and the determination of individual anthropometric data might have led to a certain measuring inaccuracy with regard to the sprint analysis. The use of a body scanner would have provided more accurate data concerning segment length and moments of inertia. In addition, we are aware of the fact that, although the inverse-dynamic modeling approach is a well-accepted biomechanical method, its capacity to provide quantitative information about muscle function is limited.[26] This is especially valid for the swing phase in sprinting, where just moments of inertia enter the calculation of joint mechanics.[9,11,13] Future studies should evaluate the effects of shoe mass on knee and hip joint mechanics during the late swing phase of maximal sprints. Furthermore, upcoming comparisons of sprint and isokinetic parameters must be performed with the same computation and body models to improve consistency.

Prospective studies dealing with the prevention and prognosis of sprint-related injuries ought to provide additional information about the practicability and suitability of DCRe and knee flexor-hip extensor ratios.[12,18] Although hamstring injuries appear to be a knee muscle injury, the major contribution of the hamstrings to hip joint mechanics should be kept in mind.[2,13,15] Therefore, preventive exercises should imply sprint-related hip and knee joint mechanics to adequately prepare for the corresponding loads.[1,3,15]

Conclusions

Swing phase parameters and isokinetic measures were able to predict 60% of the interindividual differences of sprint velocity within a relatively narrow performance range (8.8–10.5 m/s). Fast sprinters revealed distinctive knee and hip mechanics during the late swing phase as well as strong eccentric hamstrings with a clear association to the musculo-articular requirements of the swing phase in sprinting. Knee and hip joint mechanics strongly affected each other and were significantly associated with isokinetic eccentric knee flexor tests, DCRe moments, and angles. The maximal sprints imposed considerably higher loads on the athlete's body than isokinetic exercise. Therefore, the transferability of isokinetic knee strength data to sprinting is limited due to, for example, different hip joint mechanics. However, isokinetic tests can be used to quantify specific sprint-related muscular prerequisites and constitute a useful diagnostic tool due to their predicting value to sprint performance.

Acknowledgments

The authors would like to thank all subjects who volunteered to participate in this study and demonstrated great motivation and commitment. Dr. Werner Groß-Alt deserves our sincere gratitude because his skills in informatics made these insights possible.

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