Title: Kinematic adaptations in sprint acceleration performances without and with the constraint of holding a field hockey stick

Key Words: Stride Analyses, Lower Extremity, Technique, Training Specificity, Field Sports

Authors: Maximilian M. Wdowski¹ & Marianne J.R. Gittos¹,

Affiliation: ¹Cardiff School of Sport, Cardiff Metropolitan University,
Cardiff, Cyncoed Road, Cardiff, UK. CF23 6XD

Journal: Sports Biomechanics

Submission type: Original Article

Word count: Abstract: 200 words;
Body of text: 4013 words

Submission Date: 01/11/12

Correspondence address: Mr Maximilian M. Wdowski
Cardiff School of Sport,
Cardiff Metropolitan University, Cardiff,
Cyncoed Road,
Cardiff. UK. CF23 6XD

Telephone +44 (0) 2920 50 5027

Fax: +44 (0) 2920 41 6903

Email: mawdowski@cardiffmet.ac.uk

Financial Interest: None

Abstract

The aim of this study was to investigate the technique adaptations made when performing sprint-based tasks without (free condition) and with (constrained condition) the constraints of carrying a field hockey stick. Three free and three constrained maximal sprint accelerations were performed by 18 experienced university male field hockey players (mean $\pm$ s: age 20 $\pm$ 1 years, body mass 73.3 $\pm$ 7.1 kg and stature 1.78 $\pm$ 0.05 m). An automatic motion analysis system tracked sagittal plane active marker locations (200 Hz). The mean sprint velocity during the 18-22 m (free: 8.03 $\pm$ 0.43 m/s; constrained: 7.93 $\pm$ 0.36 m/s) interval was significantly ($p=0.03$) different between free and constrained conditions. While the mean stride length and stride frequency was similar between free and constrained conditions in the 2-13 m capture volume, the free condition elicited a 0.10 m/s faster ($p=0.03$) stride velocity. Further significant differences were found between free and constrained kinematic profiles ($p\leq 0.05$) for the hip angular velocity at touchdown during the 2-12 m interval of the sprints and in the overall sprint technique coordination between free and constrained conditions. Performance and technique adaptations indicated that sprint training protocols for field sports should integrate specific equipment constraints to ensure explicit replication of the mechanical demands of the skills underpinning superior performance.

Introduction

A performer's ability to accelerate rapidly over a short sprint running distance may be a critical factor in the successful accomplishment of the performance requirements of field sports (Cronin & Hansen, 2006; Murphy, Lockie & Coutts, 2003; Sayers, 2000) but may be restricted by the imposed external constraints. A wide variety of field sports including rugby, cricket, and field hockey require the performer to carry fundamental but constraining items of equipment (e.g. a ball or stick) while performing the task objectives of the sport. For example, carrying a rugby ball over a 30 m sprint run has adversely influenced the time taken to cover the distance when compared to a sprint run performed without a ball (Grant et al., 2003; Walsh, Young, Hill, Kittredge & Horn, 2007). The addition of weights to the body has further been reported to affect performance and to incur adaptations in sprint technique (Alcaraz, Palao, Elvira & Linthorne, 2008; Cronin, Hansen, Kawamori & McNair, 2008; Ropert, Kukolj, Ugarkovic, Matavulj & Jaric, 1998), which describes the relative position and orientation of body segments as they change during the performance of a sport task.

The majority of biomechanical studies of sprint running have provided insight into maximal velocity phase of unconstrained (free) sprint running tasks. The interaction between stride length and stride frequency has traditionally been discussed as the foremost biomechanical determinant of maximal acceleration running (Hunter, Marshall & McNair, 2004). A stride has traditionally been defined (Moir, Sanders, Button & Glaister, 2007) as the period between sequential toe-off (last point of foot-ground contact) events for the same leg. While biomechanical investigations of stride-related outcomes have enhanced insight into the development of sprint running performance (Salo, Bezodis, Batterham & Kerwin, 2011), consideration of the task outcome alone has been suggested to provide an incomplete analysis of

human movement (Heiderscheit, 2000). An understanding of the associated joint and limb kinematic profiles used in sprint running has since been advocated for gaining a full insight into technique developments required to enhance performance (Gittoes & Wilson, 2010).

Early studies examining lower extremity kinematics (Mann & Sprague, 1983; Mann & Herman, 1985) suggested that an increase in forward velocity in running was associated with more rapid lower- and upper-leg velocities at touchdown. More recently, the ability to reduce braking forces in stance has been closely linked to the hip flexion and knee extension action (Kivi, Marak & Gervais, 2002). The respective authors however, suggested that the knee and hip extension actions had less influence on sprint running performance at or after toe-off. In field sports, Murphy et al. (2003) similarly suggested that a reduced knee extension at toe-off, which was potentially facilitated by the hip flexor action, elicited more rapid sprint accelerations. The use of a reduced knee extension at toe-off however contradicted preceding findings suggesting that the leg should be fully extended at toe-off during acceleration (van Ingen Schenau, de Koning & de Groot, 1994). A potential compensation by the hip joint for a reduced knee joint contribution in the stance phase of maximal velocity sprint running (Bezodis, Kerwin & Salo, 2008) has recently supported a need to further consider coordinative joint actions in sprint running analyses. Coordination has been defined (Sparrow, 1992) as either the relationship in movement responses between segments in the same limb (intra-limb coordination) or between segments on different limbs (inter-limb coordination). Coordination analyses can provide a holistic measure of technique for coaching (Irwin and Kerwin, 2007) and may enhance understanding of the mechanical determinants of sprint performance (Gittoes & Wilson, 2010).

Field hockey is an example of a sport where success has been explicitly linked to speed and agility (Anders & Myers, 2008). Field hockey players are typically required to achieve and run at full velocity for only short distances e.g. 30 m, and are constrained by the need to carrying a stick. However, training protocols have tended to use running drills completed without stick carrying and have subsequently negated potential technique adaptations incurred by the equipment constraints of a match situation. The aim of this study was to investigate the stride-based hip and knee joint technique (kinematic) adaptations in sprint acceleration performances of field hockey players executed with and without the constraint of carrying a hockey stick. Differences in the knee and hip joint coordination responses are hypothesised to exist between sprint acceleration conditions.

Methods

Participants & protocol

Eighteen participants from the University's men's hockey teams (mean $\pm$ s: age 20 $\pm$ 1 years, body mass 73.3 $\pm$ 7.1 kg and stature 1.78 $\pm$ 0.05 m) who had trained and played field hockey on a regular basis for 3-12 years, and had competed at regional level or above, were recruited for the study. Due to the different equipment requirements of Goal Keepers, outfield players only were included in the study. The study was approved by the University's' Local Research Ethics Committee and each participant was injury free and provided written informed consent prior to the onset of the data collection.

The performers, who all wore rubber soled shoes, executed a 10 minute self-guided warm up before performing maximal effort acceleration sprints over a straight line distance approximating 25 m without (free condition: three trials for each

participant) and with (constrained condition: three trials for each participant) the constraint of holding a field hockey stick. The trials were performed on a 110 m indoor athletics track in a randomised order and were separated by a minimum of four minutes rest. The trials were initiated using a protocol adapted from Murphy et al. (2003), which required the performers to stand with their right leg positioned with a slight flexion of the hip and knee joints and anterior to the left leg. In the constrained condition trials, the performers were asked to hold the hockey stick in the 'shake hands' grip described by Anders and Myers (2008). The 'shake hands grip' required the performers to carry the field hockey stick by gripping the stick half way down with their right hand and placing their left hand at the top of the stick. The hockey stick used in each trial was a medium 36.5" TK CX3.0 (TK Hockey Equipment, Pakistan).

Data collection & processing

A cartesian optoelectronic dynamic anthropometer (CODA, 6.30B-CX1 motion analysis system (Charnwood Dynamics, UK) sampling at 200 Hz was used to track two-dimensional active marker locations during the sprint running trials. The markers were located uni-laterally on the left side of the participants' body on the temple (head), the anterior superior margin of the greater trochanter (hip), the lateral epicondyle of the femur (knee), the lateral malleolus of the fibula (ankle) and the dorsal aspect of the fifth metatarsal head (toe).

As illustrated in Figure 1, three CODA scanner units were horizontally aligned 3 m perpendicular to the plane of motion at 5 m, 10 m and 20 m locations from the performers' starting location. The scanners were aligned relative to the longitudinal axis of the 110 m running track such that the y- and x-axis were defined along, and

perpendicular to the plane of motion respectively. The z-axis was defined vertically relative to the track surface. The scanners located at 5 m and 10 m created a field of view, which allowed the tracking of a minimum of 2 complete strides between 2-12 m of the run trials. Data were captured during the respective interval to allow early acceleration phase analyses. The scanner located at 20 m enabled the determination of the average running velocity of each participant during the 18-22 m interval. Successful trials were defined when active marker visibility exceeded 80% visibility for every scanner and the participant maintained a consistent sprinting style (e.g. no stumbling or dropping the field hockey stick) throughout the run.

.....Insert Figure 1 here.....

The two-dimensional y- and z-coordinate marker data were filtered with a fourth order, low-pass Butterworth filter and a cut off frequency of 10 Hz, which was determined using Winter's (1990) residual analysis. The filtered coordinate data were exported for further analysis at a maintained sample rate of 200 Hz.

Data analysis

The average y-velocity of the filtered hip marker was determined for the 5-10 m and 18-22 m intervals, to assess acceleration performance of each trial and to ensure the performers had accelerated during the trial. The relationship between average horizontal velocity of the hip marker and the quality of sprinting performance has previously been established by Mann and Herman (1985). The average sprint velocities of each participant's trials were separately derived for the 5-10 m and 18-22 m intervals. The overall acceleration performance was subsequently determined

for the free and constrained conditions as the group mean ($\pm$ s; N = 18 participants for each interval) of the average participants' sprint velocities.

For the stride (performance) characteristics, toe-off (initiation of the swing phase) and touchdown (initiation of the stance phase) were defined during the 2-12m capture volume using the previously employed kinematic definition of Bezodis, Thomson, Gittoes and Kerwin (2007), which utilized the time of the peak filtered z-acceleration of the toe marker. A stride was subsequently defined from the instant of toe-off (initial) of one foot to the instant of the following toe-off (final) event for the same foot. The stride length was determined as the y-displacement of the toe marker between the respective toe-off events. The stride frequency was correspondingly defined as the reciprocal of the duration between the initial and final toe-off events, and the stride velocity was determined as the product of the stride length and frequency.

The stride-specific lower extremity joint angle and angular velocity time profiles were exported for a minimum of two complete stride cycles for each trial. Sagittal plane joint angle profiles were determined for the left leg hip (flexion–extension) and knee (flexion–extension) as the vector angle formed between co-joined lower extremity segments, which were additionally defined using the filtered joint centre coordinate data. The angle and angular velocity time profiles were interpolated to 101 points and subsequently normalized to 100% of the respective stride time. Discrete hip and knee joint angle and angular velocity measures were obtained from the joint angle and angular velocity profiles for each stride and included the respective quantities at the instants of initial toe-off and touchdown.

The group mean ($\pm$ s) for each of the discrete stride performance and joint kinematic measures was determined as the mean (N = 18 participants) of all

participants' average stride measures obtained from the free and constrained conditions. The group ensemble ($\pm$ s) time normalised hip and knee joint angular kinematic profiles were determined as the average across each time point of the individual ensemble stride profiles derived for the respective measures. The free and constrained condition ensemble profiles were quantitatively compared by calculating the root mean squared difference (RMSD) expressed as a percentage of the range of motion for the combined conditions in the group ensemble time normalised hip and knee joint angular kinematic profiles. For the joint kinematic coordination analyses, the within-limb (left) coupling between the group ensemble hip and knee joint flexion-extension profiles was assessed using a relative motion (angle-angle) plot.

Statistical analyses

The participant's group mean for the discrete stride performance and joint kinematic measures were tested for homogeneity of variance and normality using a Levene's test and a Kolmogorov-Smirnov test, respectively (SPSS inc., Version 19). A paired-samples t-test was subsequently used to statistically compare mean condition responses for the parametric data sets, which included; average velocity between 5-10 m and 18-22 m, stride velocity, stride length, stride frequency, ankle angle at touchdown, ankle and knee angular velocity at touchdown, ankle and knee angle at toe-off, ankle, knee and hip angular velocity at toe-off, knee and hip minimum angle and knee and hip maximum angle (α level = 0.05). A Wilcoxon signed-rank test was employed to examine differences in the non-parametric measures, which included; hip angle at touchdown, hip angle at toe-off, hip angular velocity at touchdown and knee angle at touchdown (α level = 0.05). In alignment

with recent warnings regarding the application of the Bonferroni correction (Brandstätter & Kepler, 1999), no correction to the significance level was made in the analyses despite the use of multiple t-tests. To provide further information regarding any differences between the free and constrained conditions the 95% confidence interval of the mean difference was derived.

Results

Average sprint velocity

As illustrated in Figure 2, a similar ($p = 0.05$, 95% CI [-0.01, 0.11 m/s]) mean average sprint velocity was achieved between 5-10 m in the free (mean $\pm$ s: 6.79 $\pm$ 0.22 m/s) condition compared to the constrained condition (mean $\pm$ s: 6.73 $\pm$ 0.20 m/s). A more rapid ($p = 0.03$, 95% CI [0.01, 0.17 m/s]) mean average sprint velocity was achieved in the free condition (mean $\pm$ s: 8.03 $\pm$ 0.43 m/s) between 18-22 m when compared to the constrained condition (mean $\pm$ s: 7.93 $\pm$ 0.36 m/s). The mean average sprint velocity was slower ($p = 0.00$, 95% CI [-1.39, -1.09 m/s]) for the 5-10 m compared to the 18-22-m interval for both the free and constrained conditions.

.....Insert Figure 2 here.....

Stride performance

The stride performance measures for the free and constrained conditions are reported in Table 1. The stride velocity was greater ($p = 0.03$, 95% CI [0.01, 0.20 m/s]) for the free (mean $\pm$ s: 6.73 $\pm$ 0.30 m/s) compared with the constrained condition (mean $\pm$ s: 6.63 $\pm$ 0.27 m/s). While a diverse stride velocity was achieved

between the free and constrained condition for the 2-12 m capture interval, the underlying stride length and stride frequency was similar between conditions.

Discrete joint kinematics

As reported in Table 1, a greater hip extension angular velocity at touchdown ($p = 0.04$, 95% CI [0.1, 0.6 rad/s]) was observed in the free (mean $\pm$ s: 4.5 ± 1.3 rad/s) compared to the constrained condition (mean $\pm$ s: 4.1 ± 1.5 rad/s). While a smaller ($p = 0.00$, 95% CI [-3.1, -0.9°]) minimum knee angle was produced in the swing phase of the stride cycle of the free (mean $\pm$ s: $57.1\pm8.6^\circ$) compared to the constrained (mean $\pm$ s: $59.1\pm9.0^\circ$) condition, the knee joint angle at initial toe-off and touchdown were similar between conditions.

.....Insert Table 1 here.....

Continuous joint kinematics

Figure 3 shows the ensemble normalised time profile of the hip and knee joint angle for the free and constrained conditions. A similar RMSD between the free and constrained conditions was produced for the hip (1.7% of the range of motion in the group ensemble combined condition time normalised hip joint angular kinematic profile) and knee joint angle (1.8% of the range of motion in the group ensemble combined condition time normalised knee joint angular kinematic profile) profiles.

.....Insert Figure 3 here.....

Joint kinematic coordination

The coordination of the hip and knee joint techniques was examined for the free and constrained conditions by comparing the group ensemble angle-angle plots presented in Figure 4. The hip and knee joint angle-angle profiles were typically similar across the stride cycle for the free and constrained conditions. However, differences in the hip and knee joint angle interactions were evident between the free and constrained conditions at, and shortly after initial toe-off during early swing phase (event 1), approaching touchdown in the late swing phase (event 2) and around the instant of minimum knee angle (event 4) during stance. The smaller minimum knee angle achieved in the free compared to the constrained condition (Table 1) (event 4) was accompanied by free and constrained hip joint angles of $93.8 \pm 9.8^\circ$ and $95.6 \pm 7.6^\circ$, respectively.

.....Insert Figure 4 here.....

Discussion and implications

As highlighted by Anders and Myers (2008), field hockey is an example of a sport where success has been explicitly linked to speed and agility. An enhanced understanding of the biomechanics of constrained acceleration sprint running therefore has the potential to provide a valuable insight into the development of effective field sport training drills and coaching protocols. The kinematic adaptations made in sprint acceleration performances in response to the imposed equipment carrying constraints of field hockey were subsequently examined in this study.

From a performance perspective, the sport-specific constraint of holding a field hockey stick was associated with a decline in the horizontal sprint running velocity achieved between 18-22 m during an acceleration run. Acceleration was evidenced

304 by a significantly slower horizontal velocity at 5-10 m for both conditions when
305 compared to the 18-22 m interval. The decline in performance suggested that
306 straight-line, free (unconstrained) running protocols typically used in training drills
307 (e.g. Spencer, Fitzsimons, Dawson, Bishop & Goodman, 2006), may not necessarily
308 replicate the performance and mechanical demands of field hockey sprinting. Hunter
309 et al.'s (2004) adaptation of an existing deterministic model of sprint running
310 performance (Hay, 1993) suggested that the ability to create a high average velocity
311 is attributed to a combination of stride length and stride frequency developments.
312 The decline in average sprint velocity over the constrained running trials was
313 supported by a 0.10 m/s decline in average stride velocity between 2-12 m and a
314 maintained stride length and stride frequency. A reduction in stride length has
315 contrastingly been reported in constrained compared to free sprint running tasks
316 investigated for generic sports conditioning skills (Alcaraz et al., 2008; Cronin et al.,
317 2008; Lockie, Murphy & Spinks, 2003). In further contrast to the findings of this
318 study, constrained sprint running conditions have frequently been reported to have a
319 negative effect on stride frequency (Cronin et al., 2008; Lockie et al., 2003; Ropret et
320 al., 1998). The combination of a reduced stride velocity and no significant decrease
321 in stride frequency, stride length or both is in direct contrast to the mechanical model
322 of sprinting performance put forward by Hunter and colleagues (2004). A study
323 investigating constrained sprinting by Alcaraz and colleagues (2008) suggested that
324 the absence of either a reduced stride length or stride frequency was possible.
325 Although no mechanical explanation was given by Alcaraz *et al.* (2008) for the
326 consistent stride length and stride frequency, Salo et al. (2011) suggested that the
327 respective outcomes are often very dependant upon the grouping of the data, and
328 further argued that an average group-based analyses can actually mask important

issues at an individual level. The reported diversity in stride contributions to sprint running performances executed under unique constrained conditions (e.g. trailing a weighted sled; Lockie et al., 2003) compared to carrying a field hockey stick, may be underpinned by technique adaptations in stride outcomes that are specific to the task, sport and individual athlete. Future athlete-centred analyses of field hockey sprinting may subsequently be advocated to enhance insight into the skill-specific development of constrained sprint running.

In order to gain further insight into the mechanical adaptations underpinning the decline in field hockey sprint acceleration performance, an investigation of the hip and knee kinematics used in free and constrained running tasks was conducted in this investigation. Stride length development has been associated with the body segment positions achieved at toe-off (take-off) and touchdown (Hay, 1993). Studies of acceleration phase, straight-line free sprint running have previously associated an increased hip joint extension at toe-off with a longer stride length and a subsequently enhanced sprint performance with maintained stride frequencies (Hay, 1993; Hunter et al., 2004). Hip and knee extension at toe-off were similar in the free and constrained sprint running conditions, which supported the maintained stride length achieved in the presence of similar stride frequency responses. The decline in average velocity and stride velocity achieved by the performers during the constrained field hockey running conditions may therefore not be attributed to a restricted hip or knee extension at the completion of stance.

While ground reaction force investigations were precluded in this study due to restrictions in collecting multiple stride cycles, lower magnitudes of relative braking impulse have been associated with faster sprint velocities during acceleration phase sprint running (Hunter, Marshall & McNair, 2005). Early sprint running research

(Mann & Sprague, 1983) has further associated high hip joint extension angular velocities with reduced braking force at the instant of touchdown. The less rapid hip joint extension angular velocity achieved at touchdown in the constrained (4.5 rad/s) compared to the free condition (4.1 rad/s) may partially account for the less successful acceleration performance in the constrained sprint running conditions due to a heightened braking force. A further examination of the association between stride-specific hip joint extension action and accentuated braking forces in constrained sprint running is however warranted to further insight into the underlying mechanisms of superior sprint running acceleration.

The ability to maintain stride length and frequency in constrained acceleration sprint running by the performers examined in this investigation may partially be attributed to the sustained knee joint angular configuration and velocity at initial toe-off in the free and constrained running conditions. Murphy et al. (2003) suggested that a reduced knee extension at toe-off was a kinematic determinant of early acceleration in field sport performers. In contrast, this investigation suggested that the knee joint kinematics employed at the onset of the swing cycle may not be primary contributors to acceleration performances produced when carrying a field hockey stick. Furthermore, the correspondence in the RMSD derived between conditions for the individual hip (1.7%) and knee (1.8%) angular displacement profiles suggested that similar kinematic adaptations were achieved by the hip and knee joints to accommodate the equipment constraints imposed in sprint running performances of field hockey. Despite the similarity in profiles across the stride cycle, the joint-specific responses in the discrete, isolated kinematic analyses suggested a need to advocate caution in the specificity of sprint training and testing without the constraints demanded of the sport.

While isolated joint kinematic assessments have provided a valuable insight into sprint running mechanics, the movement patterns underpinning sprint running may be determined by a combination of segment interactions (Hunter et al., 2005). Recent attempts have been made to develop insight into the joint coordination patterns underpinning free sprint running (Gittoes & Wilson, 2010) but limited understanding of the joint coordination adaptations made in free and constrained conditions has been achieved. In order to gain a further understanding of the explicit role of the lower extremity technique adaptations made in field sport sprinting, the coordination of the hip and knee joint actions was qualitatively examined in this study using relative motion plots.

The hip-knee joint sagittal plane angle-angle profiles were found to be similar for the free and constrained conditions, which suggested the use of a generalised joint coordination strategy across the stride cycle in free and constrained sprint acceleration performances. However, as predicted in the hypothesis, profile discrepancies were evident at key stride cycle events between the two conditions. The more pronounced maximum knee joint flexion (minimum knee angle) in the free compared to the constrained condition swing phase was preceded and followed by a greater relative change in the knee joint and a comparable change in the hip joint configuration. Running velocity increases have previously been associated with more pronounced knee joint flexions (Novacheck, 1998), which are maximal early in the swing phase. Although hip joint technique adaptations were made between the free and constrained conditions at touchdown, a less pronounced maximal knee flexion during the swing phase and an inhibited acceleration performance was not simultaneously evident in this investigation. Previous research (Novacheck, 1998) has suggested a dominant contribution from the hip joint musculature in the swing

phase of running stride cycles in free conditions. A simultaneous examination of the technique and energetic adaptations made by the lower extremity joints during field sports running may accordingly be beneficial to provide an extended insight into the specificity of straight-line free running mechanics to field sport constrained sprinting mechanics.

Conclusions

The imposed constraint of holding a stick in field hockey may elicit a decline in sprint acceleration performance in response to an inhibited stride velocity when compared to free running. Technique adaptations to the hip joint at the onset of the stance phase, and the maximum flexion of the knee joint during mid-swing may contribute to performance discrepancies achieved between sprint running tasks. The diverse kinematic responses made by field hockey players to constrained and free sprint acceleration tasks potentially supported the wider integration of sprint training drills that employ the respective training protocols e.g. rugby union. The use of task- and sport-specific sprint drills, such as performing sprint protocols while carrying a hockey stick, may improve the specificity of training in field sports by allowing an explicit replication of the mechanical demands of the skills underpinning superior performance within the sport.

References

- Anders. E., & Myers. S. (2008). *Field Hockey; Steps to Success* (2nd Edition). Leeds: Human Kinetics.
- Alcaraz, P. E., Palao, J. M., Elvira, J. L. L., & Linthorne, N. P. (2008). Effects of 3 different types of resisted sprint training devices on the kinematics of sprinting at maximum velocity. *Journal of Strength and Conditioning Research*, 22, 890-897.
- Bezodis, I.N., Kerwin, D.G., & Salo, A.I.T. (2008). Lower limb mechanics during the support phase of maximum velocity sprint running. *Medicine and Science in Sports and Exercise*, 40, 707–715.
- Bezodis, I., Thomson, A., Gittoes, M., & Kerwin, D. (2007). Identification of instants of touchdown and takeoff in sprint running using an automatic motion analysis system. *Motion Times*, 1-08, 2-3.
- Brandstätter, E. & Kepler, J. (1999). Confidence Intervals as an alternative to significance testing. *Methods of Psychological Research Online*, 4, 33-46.
- Cronin, J., & Hansen, K. (2006). Resisted sprint training for the acceleration phase of sprinting. *Strength and Conditioning Journal*, 28, 42–51.
- Cronin, J., Hansen, K., Kawamori, N. & McNair, P. (2008). Effects of weighted vests and sled towing on sprint kinematics. *Sports Biomechanics*, 7, 160-172.
- Gittoes, M. J. R., & Wilson, C. (2010). Intralimb joint coordination patterns of the lower extremity in maximal velocity phase sprint running. *Journal of Applied Biomechanics*, 2, 188-195.
- Grant, S. J., Oommen, G., McColl, G., Taylor, J., Watkins, L., Friel, N., Watt, I., & McLean, D. (2003). The effect of ball carrying method on sprint speed in rugby union football players. *Journal of Sports Sciences*, 21, 1009-1015.

449 Hay. J. G. (1993). *The Biomechanics of Sports Techniques* (4th edition). London:
450 Prentice-Hall International Ltd.

451 Heiderscheit, B. C. (2002). Variability of stride characteristics and joint coordination
452 among individuals with unilateral patellofemoral pain. *Journal of Applied*
453 *Biomechanics*, 18, 110-121.

454 Hunter, J. P., Marshall, R. N., & McNair, P. J. (2004). Interaction of step length
455 and step rate during sprint running. *Medicine and Science in Sport and Exercise*, 36,
456 261-271.

457 Irwin, G., & Kerwin, D. G. (2007). Inter-segmental coordination in progressions for
458 the longswing on high bar. *Sports Biomechanics*, 6, 131-144.

459 Kivi, D. M. R., Marak, B. K., & Gervais, P. (2003). A kinematic analysis of high-speed
460 treadmill sprinting over a range of velocities. *Medicine and Science in Sport and*
461 *Exercise*, 34, 662-666.

462 Lockie, R. G., Murphy, A. J., & Spinks, C. D. (2003). Effects of resisted sled towing
463 on sprint kinematics in field-sport athletes. *Journal of Strength and Conditioning*
464 *Research*, 17, 760-767.

465 Mann, R.V., & Herman, J. (1985). Kinematic analysis of Olympic sprint performance:
466 Men's 200 meters. *International Journal of Sport Biomechanics*, 1, 151-162.

467 Mann, R., & Sprague, P. (1983). Kinetics of sprinting. *Track and Field Quarterly*
468 *Review*, 83, 4-9.

469 Mero, A., Komi, P. V., & Gregor, R. J. (1992). Biomechanics of sprint running. *Sports*
470 *Medicine*, 13, 376-392.

471 Murphy, A. J., Lockie, R.G., & Coutts, A. J. (2003). Kinematic determinants of early
472 acceleration in field sport athletes. *Journal of Sports Science and Medicine*, 2,
473 145-150.

474 Novacheck, T. F. (1998). The biomechanics of running. *Gait and Posture*, 7, 77-95

475 Salo, A. I. T., Bezodis, I. N., Batterham, A. M., & Kerwin, D. K. (2011). Elite sprinting:
476 are athletes individually step-frequency or step-length reliant? *Medicine and Science*
477 *in Sports and Exercise*, 43, 1055-1062.

478 Sayers, M. (2000). Running techniques for field sport players. *Sports Coach*, 23, 26–
479 27.

480 Sparrow, W. A. (1992). Measuring changes in coordination and control. In
481 *Approaches to the study of motor control and learning* (edited by J.J. Summers).
482 Amsterdam: Elsevier Science.

483 Spencer, M., Fitzsimons, B., Dawson, B., Bishop, D., & Goodman, C. (2006).
484 Reliability of a repeated-sprint test for field-hockey. *Journal of Science and Medicine*
485 *in Sport*, 9, 181-184.

486 van Ingen Schenau, G. J., de Koning, J. J., & de Groot, G. (1994). Optimisation of
487 sprinting performance in running, cycling and speed skating. *Sports Medicine*, 17,
488 259-275.

489 Walsh, M., Young, B., Hill, B., Kittredge, K., & Horn, T. (2007) the effect of ball-
490 carrying technique and experience on sprinting in rugby union. *Journal of Sports*
491 *Sciences*, 25, 185-192.

492 Winter, D. A. (1990). *Biomechanics and motor control of human movement*. New
493 York: Wiley & Sons.

494

Table 1. Mean ($\pm$ s) discrete stride performance and joint kinematic measures between 2-12 m of free and constrained sprinting trials (N = 18).

Kinematic Measure	Free	Constrained	95% CI
Stride frequency (Hz)	2.18 $\pm$ 0.11	2.18 $\pm$ 0.11	-0.20, 0.20
Stride length (m)	3.10 $\pm$ 0.20	3.05 $\pm$ 0.17	-0.00, 0.09
Stride velocity (m/s)	6.73 $\pm$ 0.30	6.63 $\pm$ 0.27*	0.01, 0.20
Initial toe-off knee angle (°)	144.2 $\pm$ 4.6	144.1 $\pm$ 4.4	-0.6, 0.7
Initial toe-off hip angle (°)	148.1 $\pm$ 18.7	147.6 $\pm$ 17.8	-0.7, 1.7
Initial toe-off knee angular velocity (rad/s)	-0.8 $\pm$ 1.1	-0.7 $\pm$ 0.8	-0.3, 0.1
Initial toe-off hip angular velocity rad/s)	5.6 $\pm$ 0.9	5.7 $\pm$ 0.8	-0.4, 0.1
Touchdown knee angle (°)	127.5 $\pm$ 6.8	126.9 $\pm$ 8.1	-1.3, 2.4
Touchdown hip angle (°)	96.9 $\pm$ 19.7	95.6 $\pm$ 19.4	-0.5, 3.2
Touchdown knee angular velocity (rad/s)	3.9 $\pm$ 2.8	3.5 $\pm$ 2.9	-0.2, 0.9
Touchdown hip angular velocity (rad/s)	4.5 $\pm$ 1.3	4.1 $\pm$ 1.5*	0.1, 0.6
Maximum hip angle during entire stride (°)	163.1 $\pm$ 7.8	164.1 $\pm$ 4.8	-3.4, 1.6
Minimum hip angle during entire stride (°)	93.8 $\pm$ 9.8	95.6 $\pm$ 7.6	-5.6, 2.0
Minimum knee angle during entire stride (°)	57.1 $\pm$ 8.6	59.1 $\pm$ 9.0*	-3.1, -0.9
Maximum knee angle during entire stride (°)	145.9 $\pm$ 6.0	146.0 $\pm$ 5.8	-0.9, 0.8

*Significant difference between free and constrained condition ($p \leq 0.05$).

95% CI represents the confidence interval (95%) of the differences between condition means

Full hip and knee extension is represented by an angle of 180°. A positive angular velocity represents extension of the hip and knee.

Figure 1. Schematic representation of the data collection set-up. The capture volume for the stride performance and lower limb joint kinematic analyses is highlighted by the light grey zone (2-12 m).

Figure 2. Mean ($N = 18$) average sprint velocity ($\pm s$) between the 5-10 m and 18-22 m interval for the free (grey) and constrained (white) conditions. *Significant difference between the free and constrained conditions ($p \leq 0.05$).

Figure 3. Group ensemble time normalised (a) hip and (b) knee joint angle during a complete stride pattern from initial toe-off to final toe-off between 2-12 m. The grey line indicates free condition and the dashed line indicates the constrained condition.

Figure 4. Group ensemble hip and knee joint angle-angle plot for the entire sagittal plane movement pattern of a stride from initial toe-off to final toe-off between 2-12 m for the free (grey) and constrained (black) condition. The direction of the movement is anti-clockwise.

530 **Figures**
531
532 Figure 1
533

535 Figure 3
536

537 Figure 4
538