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EFFECTS OF A SAND RUNNING SURFACE ON THE KINEMATICS OF SPRINTING AT MAXIMUM VELOCITY

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ABSTRACT: Performing sprints on a sand surface is a common training method for improving sprint-specific strength. For maximum specificity of training the athlete's movement patterns during the training exercise should closely resemble those used when performing the sport. The aim of this study was to compare the kinematics of sprinting at maximum velocity on a dry sand surface to the kinematics of sprinting on an athletics track. Five men and five women participated in the study, and flying sprints over 30 m were recorded by video and digitized using biomechanical analysis software. We found that sprinting on a sand surface was substantially different to sprinting on an athletics track. When sprinting on sand the athletes tended to 'sit' during the ground contact phase of the stride. This action was characterized by a lower centre of mass, a greater forward lean in the trunk, and an incomplete extension of the hip joint at take-off. We conclude that sprinting on a dry sand surface may not be an appropriate method for training the maximum velocity phase in sprinting. Although this training method exerts a substantial overload on the athlete, as indicated by reductions in running velocity and stride length, it also induces detrimental changes to the athlete's running technique which may transfer to competition sprinting.

KEY WORDS: **biomechanics, kinematic analysis, speed training, sprinting**

INTRODUCTION

The ability to achieve a high maximum sprinting velocity is a strong determinant of success in the sprinting and jumping events in athletics [11]. High-intensity strength training exercises with free weights and machines can improve the strength of an athlete's musculature in the hips, quadriceps and hamstrings, and hence increase the athlete's maximum sprint velocity [5,9]. However, many coaches believe that a sprint training programme should also include strength-specific exercises where the athlete performs the sport movement with added resistance [4,5,6,24]. Alcaraz and colleagues [1] showed that towing a weighted sled, towing a parachute, and wearing a weight belt are appropriate strength-specific methods for training the maximum velocity phase of sprinting. These training methods exert a substantial overload on the athlete (as indicated by reductions in horizontal velocity and stride length) but do not induce detrimental changes in the athlete's sprinting technique as long as the load in the exercise is not too great.

Sand sprinting is another common training method used to develop sprint speed [26]. The sand moves underfoot during the ground contact phase of the stride and so the athlete receives a greater training stimulus through the extra work that is performed on the sand. However, it is currently not known whether the athlete's movement patterns during sand sprinting are the same as those during sprinting on an athletics track. Among sprint coaches there is a concern that sprinting on an unstable sand surface may induce detrimental changes in technique that will transfer to competition performances [14]. In particular, coaches are concerned that sand sprinting may induce 'sitting', where the athlete has lower hips during the ground contact phase of the stride and an excessive forward lean in the trunk. Such detrimental changes in technique are seen in sled-towing exercises when the load on the sled is too high [19] and it is feared that similar changes may also be evident in sand sprinting.

In the present study we compared the kinematics of sprinting at maximum velocity on a dry sand surface to sprinting on a synthetic athletics track. The aim was to establish whether sand sprinting is an appropriate exercise for training the maximum velocity phase of sprinting in that it produces an overload on the athlete without inducing detrimental changes in sprinting technique.

MATERIALS AND METHODS

A quasi-experimental intra-subject cross-sectional design was used. The independent variables were the two running conditions: sprinting on a synthetic athletics track and sprinting on a sand surface. The dependent variables were the horizontal and vertical velocities of the athlete's centre of mass, the stride length, the stride frequency, the joint and segment angles, the joint angular velocities, and the landing and take-off distances [1]. Studies on sprinting at maximum velocity have shown that these variables can be used to discriminate between good and poor sprinting technique [17,22].

The present study examined sprinting by both men and women. However, the men and women were analysed separately because there are known differences in sprinting technique between genders that arise from differences in stature and muscular strength. In particular, men tend to have a substantially greater horizontal velocity and stride length than women [1,12,15]. Men also tend to have a greater stride frequency, and this is reflected in the greater angular velocities of their joints. In contrast, men and women tend to use similar joint ranges of motion and tend to have similar body segment angles at key instants during the stride (e.g., at touchdown, mid-stance, and take-off).

In the present study the participants wore sprint shoes when sprinting on the synthetic athletics track, but were barefoot when sprinting on the sand surface. Different footwear were examined on the two surfaces so as to be consistent with the footwear most often used during training on the two surfaces and hence increase the ecological validity of the study. Studies have shown that differences in technique between barefoot and shod running are relatively small [8,23].

Five men and five women volunteered to participate in the study (Table 1). The participants were active competitive athletes who specialized in the 100-m and 200-m sprints, and all had previously used sand sprinting in their training. On average, the men were 0.17 m taller and 16 kg heavier, and had a best 100-m performance that was 1.6 s faster than the women. The study was approved by the Human Subjects Ethics Committee of Universidad Católica San Antonio de Murcia, the participants were informed of the procedures and inherent risks prior to their involvement, and written consent to participate was obtained.

TABLE 1. GENERAL CHARACTERISTICS OF THE PARTICIPANTS (MEAN ± SD)

Variable	Men (n = 5)	Women (n = 5)	Cohen's d
Age (years)	21 ± 6	19 ± 2	0.5
Height (m)	1.81 ± 0.08	1.64 ± 0.05	2.8*
Body mass (kg)	77 ± 8	61 ± 5	2.7*
Best 100m sprint performance (s)	11.0 ± 0.4	12.6 ± 0.3	5.1*
Training experience (years)	8 ± 2	9 ± 2	0.6

Note: * = large effect size (d ≥ 0.8).

The study was conducted over two sessions (a 'track' session, and a 'sand' session one week later) during the pre-season phase of the athlete's training. The track sprinting trials were conducted on a synthetic athletics track (Rekortan M99, ATP Corp, Harmony, PA, USA) in an outdoor athletics stadium. Participants wore their own athletic training clothes and spiked sprint shoes. Before commencing the trials the participants performed a sprint-specific warm-up consisting of 8 minutes of running with a heart rate of 140 bpm, 8 minutes of active stretching, 10 minutes of running technique exercises, and 2–4 submaximal and maximal short sprints.

The sprint trials were 30-m flying sprints at maximum intensity using a run-in distance of 20 m from a standing start. An unlimited rest period was given between trials to minimize the effects of fatigue on sprint performance. The rest period typically lasted about 6 minutes, which is sufficient for full recovery from repeated maximal sprints of short duration [10]. The wind velocity for all trials was measured using a wind gauge (Standar, Cantabrian, Cambridge, UK), and trials in which the wind was not between –2 m/s and 2 m/s were repeated. For wind velocities within this range the wind produces a change in 30-m sprint time of less than ±1% from a zero-wind result [20].

A similar procedure was used for the sand sprinting trials. The sand running surface was a level stretch of coastal beach above the high water mark. The sand grains had an average diameter of about 0.25 mm and the density of the sand was about 1530 kg/m^3.

All the sprints were recorded using a Canon XM-1 digital miniDV video camera (Canon Inc., Tokyo, Japan) operating at 50 Hz. The camera was mounted on a rigid tripod at a height of 1.3 m, and placed at a distance of 20 m from the middle of the athlete's lane. The optical axis of the camera was perpendicular to the direction of running, and the field of view of the camera was zoomed so that the athlete was visible in a 5-m wide region about the 20-m mark of the 30-m flying sprint. This field of view ensured that a complete running cycle (2 steps) would be recorded. The movement space was calibrated with two 2-m high poles that were placed along the midline of the athlete's lane and 5 m apart. Photoelectric cells (BioMedic, Barcelona, Spain) were placed at the start and finish of the 30-m flying sprint to record the sprint times.

Kwon3D biomechanical analysis software (Visol, Cheolsan-dong, Korea) was used to analyse the video images of the trials. Twenty-two body landmarks that defined a 14-segment model of the athlete were manually digitized in each image. The segmental data used were those proposed by de Leva [7]. The digitized images were interpolated to 100 Hz using fifth-order splines and the two-dimensional coordinates of the body landmarks and the athlete's centre of mass were calculated using the direct linear transform (DLT) algorithm. Coordinate data were smoothed using a second-order Butterworth digital filter with a cut-off frequency of 6 Hz and the velocity of the athlete's centre of mass and joint angular velocities were calculated from the coordinate data using the finite differences method. The kinematic variables were measured at three instants during the stride: touchdown (T_{down}), mid-stance (T_{mid}), and take-off (T_{off}). The instant of touchdown was the first frame in which the athlete's foot was in contact with the ground, the mid-stance was the frame nearest to when the athlete's centre of mass passed directly over the toe of the foot, and the instant of take-off was the first frame in which the athlete's foot was no longer in contact with the ground [1].

All digitizing was performed by the same operator to maximize the consistency of the dependent variables. The reliability of intra-participant digitizing and inter-participant digitizing was very high. An intra-class correlation coefficient value of 0.999 was obtained when three instants of the same video sequence were digitized five times, and an intra-class correlation coefficient value of 0.998 was obtained when two researchers digitized three instants of the same sequence.

One trial by each participant for each sprint condition was analysed, and the data for men and women were analysed separately. Scatterplots of all variables were examined to identify those variables which had substantial differences between the two sprint conditions. Coordination of the athlete's lower limbs was investigated by plotting time traces and angle-angle diagrams of the body joints [2]. We mainly used graphs to analyse the data from this study because previous studies have shown that changes in sprinting technique are mostly obvious through a visual inspection of the data. Studies on differences between athletes of varied ability and on the changes induced by sled towing led us to be concerned with changes of at least the standard deviation in the measure [1,19,21,22,25].

Although we used a graphing emphasis in our data analysis, a statistical analysis was also performed. Because of the low number of participants in this study, a Wilcoxon test (SPSS 13.0, SPSS Inc., Chicago, IL) was used to compare the two sprinting conditions. Significance was set at $\alpha \le 0.05$. For each variable, the effect size (Cohen's d, using a pooled standard deviation) was calculated to determine the strength of the difference between the two conditions [3]. In this study we were interested in 'large' differences in sprinting technique between the two conditions, where $d \ge 0.8$.

RESULTS

The body configurations and joint angular velocities observed in the trials on the athletics track were similar to those in other studies of experienced sprinters, and similar values were observed for the men and the women [1,22]. The women tended to have a slower average horizontal velocity, a shorter stride length, and a slightly lower stride frequency than the men. However, these differences were expected as they are believed to arise from the lesser muscular strength of the women relative to the men [12]. The women also tended to have a slightly lower centre of mass during the ground contact phase of the stride, but again this was mostly a reflection of their shorter stature rather than differences in body configuration.

For both the men and the women, the sand surface produced a substantially slower 30-m average velocity than sprinting on an athletics track (Figure 1). On average, the percentage decrease in velocity was 15.8% ($P = 0.002$, $d = 3.6$) for the men and 12.4% ($P = 0.002$, $d = 2.7$) for the women. In sprinting, the athlete's horizontal velocity is determined by the product of their stride length and stride frequency [11]. For the athletes in this study the decrease in horizontal velocity arose mainly through a decrease in stride length as their stride frequency tended to be the same on both surfaces (Figure 1). The substantial decreases in velocity and stride length when sprinting on a sand surface are indirect indicators that this training exercise produces a strong training stimulus to the athlete.

The sand surface did not produce substantial changes to the joint and segment angles and joint angular velocities in the athlete's upper limbs. However, substantial changes in joint angles and joint angular velocities were observed in the trunk and lower limbs. The main differences in the athlete's body configuration during the ground contact phase are illustrated in Figure 2. In sand sprinting the athletes tended to 'sit' during the ground contact phase of the stride, with a lower centre of mass and a greater forward lean in the trunk (Figure 3). The athletes also had less extension of the hip joint at the end of the support phase.

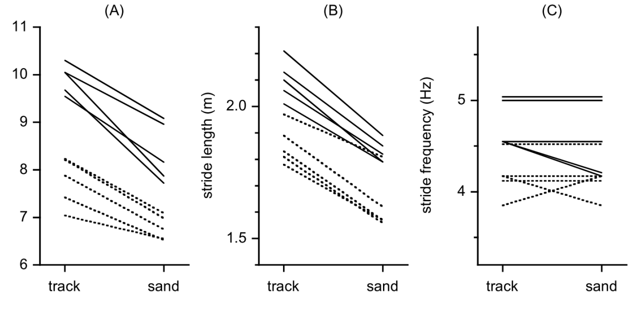

FIG. 1. THESE PLOTS SHOW THE DIFFERENCES IN STRIDE VARIABLES BETWEEN SPRINTING ON AN ATHLETICS TRACK AND SPRINTING ON SAND: (A) RUNNING VELOCITY, (B) STRIDE LENGTH, AND (C) STRIDE FREQUENCY. DATA FOR EACH OF THE 10 PARTICIPANTS ARE SHOWN, WITH MEN AND WOMEN INDICATED BY SOLID LINES AND DASHED LINES RESPECTIVELY. THE SUBSTANTIAL DECREASES IN VELOCITY AND STRIDE LENGTH INDICATE THAT SAND SPRINTING PRODUCES A STRONG OVERLOAD ON THE ATHLETE.

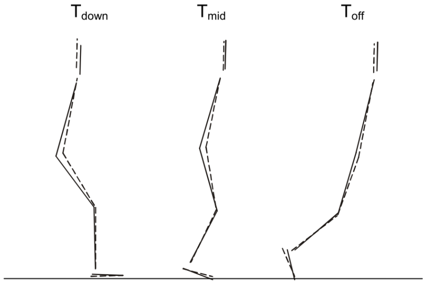

FIG. 2. THESE DIAGRAMS COMPARE THE BODY CONFIGURATIONS BETWEEN SPRINTING ON AN ATHLETICS TRACK (DASHED LINES) AND SPRINTING ON SAND (SOLID LINES). BODY POSITIONS ARE SHOWN AT THE INSTANTS OF TOUCHDOWN (T_{DOWN}), MID-STANCE (T_{MID}), AND TAKE-OFF (T_{OFF}), AND DATA ARE AN AVERAGE OF THE FIVE MEN. WHEN SPRINTING ON SAND THE ATHLETES TENDED TO 'SIT' DURING THE GROUND CONTACT PHASE OF THE STRIDE, WITH A LOWER CENTRE OF MASS, A GREATER FORWARD LEAN IN THE TRUNK, AND AN INCOMPLETE EXTENSION OF THE HIP JOINT AT TAKE-OFF.

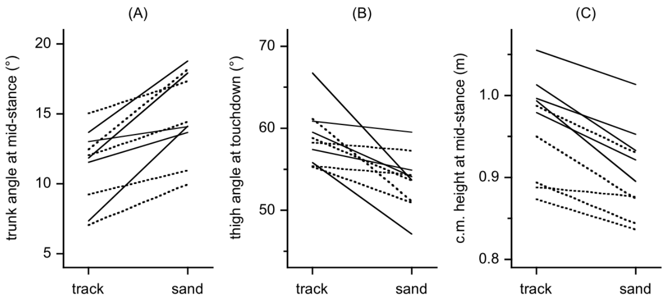

FIG. 3. THESE PLOTS SHOW THE DIFFERENCES IN BODY SEGMENT ANGLES BETWEEN SPRINTING ON AN ATHLETICS TRACK AND SPRINTING ON SAND: (A) FORWARD TRUNK LEAN AT MID-STANCE, (B) ANGLE OF THE THIGH TO THE HORIZONTAL AT TOUCHDOWN, AND (C) HEIGHT OF THE ATHLETE'S CENTRE OF MASS AT MID-STANCE. DATA FOR EACH OF THE 10 PARTICIPANTS ARE SHOWN, WITH MEN AND WOMEN INDICATED BY SOLID LINES AND DASHED LINES RESPECTIVELY. WHEN SPRINTING ON SAND THE ATHLETES TENDED TO 'SIT' DURING THE GROUND CONTACT PHASE OF THE STRIDE, WITH A LOWER CENTRE OF MASS AND A GREATER FORWARD LEAN IN THE TRUNK. THE REDUCTION IN THE THIGH ANGLE AT TOUCHDOWN IS AN INDIRECT INDICATOR OF A LOWER CENTRE OF MASS AT TOUCHDOWN.

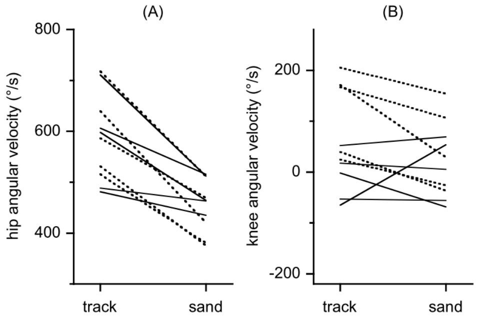

FIG. 4. THESE PLOTS SHOW THE DIFFERENCES IN JOINT ANGULAR VELOCITIES BETWEEN SPRINTING ON AN ATHLETICS TRACK AND SPRINTING ON SAND: (A) HIP ANGULAR VELOCITY AT MID-STANCE, AND (B) KNEE ANGULAR VELOCITY AT MID-STANCE. DATA FOR EACH OF THE 10 PARTICIPANTS ARE SHOWN, WITH MEN AND WOMEN INDICATED BY SOLID LINES AND DASHED LINES RESPECTIVELY. THE REDUCTION IN HIP ANGULAR VELOCITY AT MID-STANCE IS ROUGHLY PROPORTIONAL TO THE REDUCTION IN RUNNING VELOCITY EXPERIENCED WHEN SPRINTING ON SAND. KNEE ANGULAR VELOCITY AT MID-STANCE WAS NOT EXPECTED TO CHANGE SUBSTANTIALLY IN RESPONSE TO THE REDUCTION IN RUNNING VELOCITY.

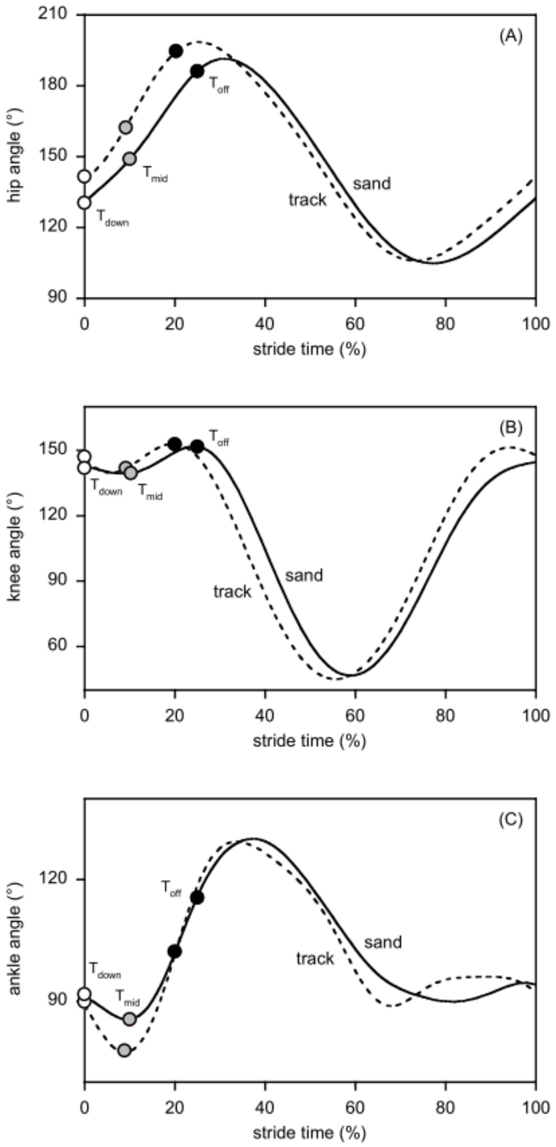

FIG. 5. THESE PLOTS COMPARE THE JOINT ANGLES OF THE SUPPORT LEG BETWEEN SPRINTING ON AN ATHLETICS TRACK AND SPRINTING ON SAND: (A) HIP ANGLE, (B) KNEE ANGLE, AND (C) ANKLE ANGLE. DATA ARE THE AVERAGE OF ALL TEN PARTICIPANTS, AND HAVE BEEN NORMALIZED TO THE TOTAL STRIDE TIME. KEY TIMES DURING THE GROUND CONTACT PHASE OF THE STRIDE ARE INDICATED (TOUCHDOWN, MID-STANCE, AND TAKE-OFF). COMPARED TO SPRINTING ON AN ATHLETICS TRACK, SAND SPRINTING HAD A PHASE SHIFT OF ABOUT 5% OF THE STRIDE DURATION.

When sprinting on sand the athletes in this study had a substantially lower hip angular velocity at mid-stance, but the angular velocities of the knee and ankle were almost unaffected by the running surface (Figure 4). A simple mechanical model of sprinting led us to expect that the effective angular velocity of the athlete's support leg (which produces the forward thrust) should change in direct proportion to any change in the athlete's horizontal velocity. For the athletes in this study the magnitude of the observed decrease in hip angular velocity (5–34%) was roughly consistent with the reduction in horizontal velocity (7–22%).

Time traces of the hip, knee, and ankle joint angles are shown in Figure 5, and the coordination of these joints is displayed as angle-angle diagrams in Figure 6. The movement patterns observed in the trials on the athletics track were similar to those in other studies of experienced sprinters, and similar patterns were observed for the men and the women [16,28]. For each running condition, all ten athletes in this study exhibited broadly similar movement patterns and so the average patterns shown in Figures 5 and 6 are representative of the individual athletes' movement patterns. Compared to sprinting on an athletics track, the time traces of the hip, knee, and ankle joint angles in the sand sprinting trials had a phase shift of about 5% of the stride duration (Figure 5).

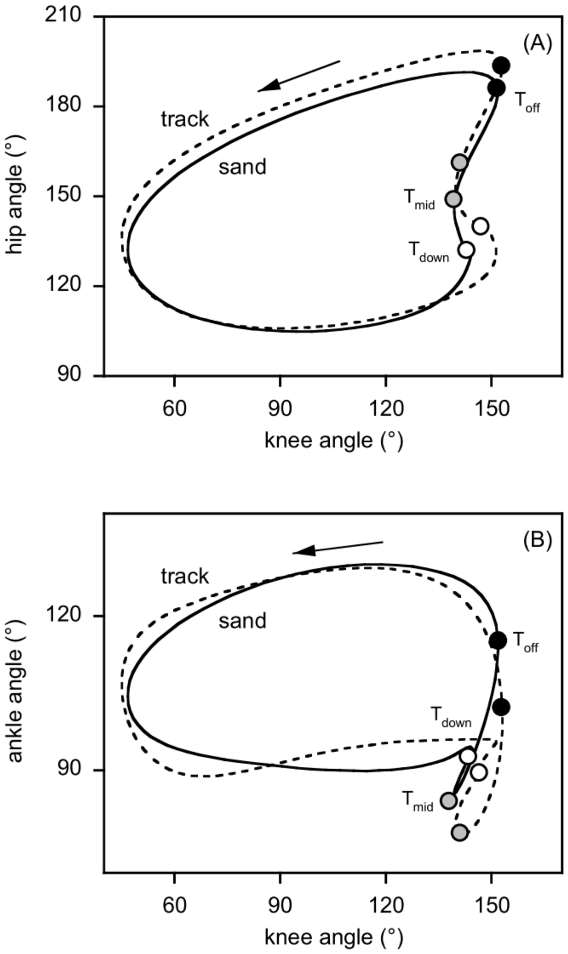

FIG. 6. THESE PLOTS COMPARE THE JOINT COORDINATION OF THE SUPPORT LEG BETWEEN SPRINTING ON AN ATHLETICS TRACK AND SPRINTING ON SAND: (A) HIP–KNEE COUPLING, AND (B) ANKLE–KNEE COUPLING. DATA ARE THE AVERAGE OF ALL TEN PARTICIPANTS, AND KEY TIMES DURING THE GROUND CONTACT PHASE OF THE STRIDE ARE INDICATED (TOUCHDOWN, MID-STANCE, AND TAKE-OFF). WHEN SPRINTING ON SAND THE PARTICIPANTS HAD LESS HIP EXTENSION.

DISCUSSION

When sprinting on a sand surface the athlete's horizontal velocity and stride length were expected to be reduced because some of the energy generated by the athlete is dissipated in the sand. When sprinting on an athletics track the athlete exerts a horizontal force on the ground to accelerate the body forwards and overcome air resistance. The athlete also exerts a vertical force so as to propel the body upwards and produce a flight phase. However, when sprinting on a sand surface the sand moves slightly at each footfall and so some of the energy generated by the athlete during the ground contact phase is dissipated in the sand rather than going into moving the athlete's centre of mass [18]. This energy loss reduces the athlete's horizontal take-off velocity and hence reduces the athlete's sprint velocity. The lower horizontal take-off velocity means that the athlete also travels a shorter forwards distance during the flight phase of the stride and so the athlete's stride length is reduced.

A sand surface was also expected to reduce the athlete's stride frequency, but only slightly. Because the athlete maintains nearly the same movement patterns and ranges of motion during the ground contact phase of the stride, the lower horizontal velocity on a sand surface means that the athlete takes longer to perform these movements and hence has a longer ground contact time. In contrast, the dissipation of energy in the sand does not affect the time taken for the athlete to perform the leg movements during the flight phase of the stride. The combined result of a longer ground contact time and unchanged flight time is a longer stride duration (i.e., a reduced stride frequency). Because in sprinting the ground contact time is only about one third of the total stride time [29], the relative change in the stride frequency is only about one third of the relative change in horizontal velocity. Therefore, the expected overall result when sprinting on a sand surface is a substantial reduction in the athlete's horizontal velocity and stride length, and a slight reduction in the athlete's stride frequency (Figure 1).

Causes of the changes in movement patterns

Close examination of the video images revealed that the phase shifts of the hip, knee, and ankle joint angle patterns when sprinting on a sand surface (Figure 5) were due to the deformation of the sand surface and the downwards and forwards movement of the foot early in the ground contact phase. There was a time delay after touchdown before the athlete's leg was able to effectively support the body and so the 'effective' instant of touchdown was a few milliseconds after first contact with the sand. Pinnington and colleagues [27] observed similar phase shifts in the movement patterns of the lower limb when comparing submaximal running on a firm surface with running at the same speeds (2.2 and 3.0 m/s) on a soft, dry sand surface.

In the present study the greater forward lean observed when sprinting on a sand surface was an important difference to sprinting on an athletics track. Mann and Herman [22] noted that elite sprinters run in a more upright position than good sprinters, and therefore we suspect that coaches should avoid using training exercises that induce and reinforce an excessive forward lean. The reduced leg extension when sprinting on a sand surface was another important difference. On a sand surface the athlete cannot exert large horizontal forces during the leg extension phase because the sand deforms and the foot moves backwards. The athlete adapts to this unstable surface by using a reduced range of leg extension during the drive phase of the stride.

Suitability of a soft, dry sand surface

The desired outcome when sprint training on a sand surface is a reduction in horizontal velocity without inducing substantial changes in the athlete's technique. However, for the athletes in our study, sprinting on a dry sand surface produced substantial and important detrimental changes in technique. Similar detrimental changes in technique are seen in sled towing exercises when the load on the sled is excessive [19]. Many coaches believe that the athlete should not use exercises that induce excessive changes in the athlete's technique when training in or near to the competition season. It is feared that such changes will be transferred to the athlete's technique when performing competition sprints on an athletics track. Sand sprinting may, however, be an appropriate training exercise for the off-season, as long as there is sufficient time for the athlete to re-learn the correct sprinting movement patterns before the start of the competition season. The results from this study suggest that sand sprinting may be more appropriate as a 'general development' exercise for the off-season, rather than as a strength-specific exercise for the competition season [14,26,30].

CONCLUSIONS

This study showed that sand sprinting may not be an appropriate exercise for training the maximum velocity phase in sprinting. Although this training method exerts a substantial overload on the athlete, as indicated by reductions in horizontal velocity and stride length compared to unloaded sprinting, it also induces undesirable changes to the athlete's sprinting technique. The athlete tends to 'sit' during the ground contact phase of the stride, with a lower centre of mass, a greater forward lean in the trunk, and an incomplete extension of the hip joint at take-off.

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Conflicts of Interest Declaration

The authors do not have any conflicts of interest.

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