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Changes in Leg Strength and Kinematics with Uphill - Downhill Sprint Training

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ABSTRACT This study examined the effects of an 8-week uphill-downhill sprint training programme on the force generation capacity of leg muscles. Twenty-four university students were randomly allocated to one of two training groups (combined uphill–downhill and horizontal) and a control group. The combined training method produced significant improvements in maximal isometric force (7.1%) and rate of force production (≈ 25%) of the knee flexor muscles ($p<0.05$). The combined training was also significantly more effective in improving the maximum sprinting speed (5.9%, $p<0.05$) and associated kinematic variables. In particular, the propulsive phase of contact decreased significantly by 17% ($p<0.05$) indicating a link between the improved rate of force production during the isometric test and the rate of production of propulsive forces during sprinting. The increased capacity of the leg flexor muscles to generate force appears to contribute to the improvement of sprinting speed perhaps due to a more efficient muscle function during the support phase of the stride.

Key words: Lower-Limb Kinematics, Rate of Force Production, Running on Sloping Surface, Sprint Training Program

INTRODUCTION

Running on sloping surfaces is widely used in training for sprint running as a way to create additional stimuli for speed improvement. Regarding acute neuromechanical effects of running on slopes, some previous studies [1, 2] have demonstrated enhanced mechanical loading applied to the hip, knee and ankle extensors during uphill running (lower speed ~$4.5\ m\cdot s^{-1}$), whereas Slawinski [3] showed a decreased activation of the hamstrings muscles during contact phase (running at $6.28\ m\cdot s^{-1}$) on a ~3° uphill slope. The same was observed for the vastus lateralis, but only for the concentric phase of the ground contact, whereas no differences occurred during the eccentric phase. Conversely, Gottschall and Kram [4] showed an increase in the concentric impulse and a decrease in eccentric impulse during similar uphill running conditions, while during downhill running the pattern was reversed with high braking impulses accompanied by large vertical impact forces. Nevertheless, the acute changes in external forces, muscle activation and loading during uphill and downhill sprinting need further investigation - by employing higher running speeds that correspond to maximum running speed (MRS) values - to clarify consistent patterns of contribution for each joint during the ground braking and propulsive phases, but also during the flight part of the stride.

Regarding acute performance effects, sprinting maximally on a 3° downhill slope has been shown to produce 8.4% faster MRS ($p<0.05$), whereas sprinting on a 3o uphill slope produced 2.9% slower MRS ($p<0.05$) when compared to horizontal sprinting [5]. Longer term observations have shown that training on downhill slopes (3˚) for 6 weeks produced significant improvements in MRS and step rate of 1.1% and 2.3% respectively ($p<0.05$) whereas under similar training conditions (duration, volume, intensity) sprinting on a 3° uphill slope did not produce any significant changes [6]. However, training for 6 or 8 weeks on combined uphill-downhill sloping surfaces (3˚) produced better improvements ($p<0.05$) for both MRS (3.5% and 4.3% respectively) and step rate (3.4% and 4.3% respectively) than any other training on sloping surfaces [6, 7]. These changes were mainly due to shorter contact time (-5.1%, $p<0.05$), which in turn was due to a shorter propulsive phase of stance (-11.5%, $p<0.05$). This was arguably the most important adaptation to training and effectively could be interpreted as an improvement in muscle power since the higher speed was achieved by the shortening of the contact time while keeping the step length unchanged. The authors [6, 7] suggested a possible link between the force generation capacity of leg muscles and the production of shorter contact time as the underlying mechanism responsible for the production of greater MRS values. However, this suggestion was theoretical, as no measurements of leg strength/power were conducted before and after the training to substantiate such claim.

The aim of this study was to evaluate the effects of an 8-week combined uphill-downhill (3˚) training programme, compared to the responses of training on the horizontal and a control condition, on the force generation capacity and power characteristics of leg muscles. In addition, as in our previous uphill-downhill studies, kinematic measurements will be employed so any changes in leg strength can be interpreted alongside changes in key kinematic variables. Therefore, the current study, by examining the mechanical responses of key leg muscle groups to uphill-downhill training, will provide an insight into the theoretical link between the increased force generation capacity of the leg muscles and both sprinting speed and kinematics. The detection of such a link will contribute to the understanding of the internal training adaptations which solely determine the changes in kinematic and performance variables observed at the end of the training period.

METHODS

SUBJECTS

Twenty-four sport and physical education students participated in this study (age 24.5 ± 2.0 years, mass 75.0 ± 9.9 kg, height 1.8 ± 0.08 m and MRS 8.15 ± 0.68 m·s-1). Written informed consent was obtained from each participant before data collection, and the study received ethical approval from the appropriate Faculty research ethics committee of Leeds Metropolitan University.

TRAINING

A wooden uphill-downhill platform was used which was covered with synthetic track surface. The width of the track surface was 1.20 m and the total distance covered was 80 m: 10m horizontal, 20 m uphill at 3° slope, 10 m horizontal, 20 m downhill at 3° slope and 20m horizontal (Figure 1). The participants were randomly assigned to three groups:

- Uphill-downhill (U+D) was trained on the uphill-downhill platform (n = 8)

- Horizontal (H) was trained on the horizontal (n = 8)

- Control (C) was the control group and did not train (n = 8).

The training groups performed 6 × 80 m sprints at maximal intensity per session, three times a week for eight weeks, where the time between repetitions (10 min) was deemed to be sufficient for the participants to recover fully. This training programme continued until the fourth week after which one repetition was added for both training groups, for each of the remaining weeks.

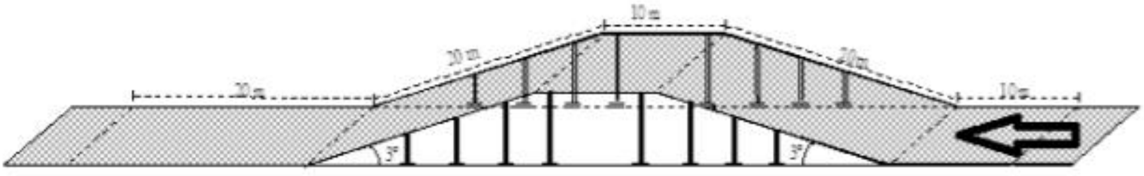

Figure 1 The uphill-downhill platform (from [6]).

35m SPRINT TESTING

Pre- and post-training tests were employed to evaluate the effects of training on the kinematic characteristics of sprint running. The participants performed three sprint runs over a 35m distance using a standing start with a 10min recovery period between repetitions in an indoor runway covered with a synthetic track surface (tartan). The best of the three trials (based on MRS values) was selected for further analysis. A Kodak EktaPro 1000 high speed video camera, sampling at 250 Hz, was used to collect recordings of the sagittal plane of a full stride (two consecutive steps). Filming was performed with the camera placed at the end of the 35 m runway and 10 m from the performance plane such that its optical axis was approximately horizontal, forming an angle of 90° with the horizontal plane of running. Running speed should be near to its maximum at 35 m after start, as evidence from the literature has showed that MRS for non-elite sprinters is achieved between 30-40 m [8]. For the digitisation process, a metal calibration frame (2 x 2 m) was filmed such that the x-axis was parallel to the horizontal and the y-axis was perpendicular to the horizontal.

ANALYSIS OF THE VIDEO DATA

The digitising system comprised of a video projector Imager LCD 15E (by General Electronic, USA), a TDS Graphic tablet and controller (x,y resolution, 0.025 mm; active area 1.20 x 0.90 m), interfaced to an IBM computer which ran the digitising programme DIGIT (Leeds Metropolitan University, UK). A standard 17-point, 14-segment model of the human performer based on the data of Dempster [9] was used to represent the human performer and to calculate the position of the centre of mass. Reliability of the digitising process was established in a previous study [5] by repeated digitising of one sprinting sequence at the same sampling frequency with an intervening period of 48 h. Contact time (CT), flight time (FT), step time (ST), step length (SL), step rate (SR) and MRS were calculated according to methods reported previously [5]. The contact phase was also divided into the braking (BP) and propulsive (PP) phases according to the vertical movements of the centre of mass, the knee, and the ankle angles during foot contact. Additionally the touchdown and take-off angles of the knee, hip, thigh, shank and trunk to running surface and that between the two thighs were calculated according to the methods reported previously [5]. Finally, the distances between the centre of mass and the foot's contact points at touchdown (DCM TD) and at take-off (DCM TO) were also calculated as previously described [5].

MAXIMAL ISOMETRIC FORCE - LEG EXTENSORS

Three maximum voluntary contractions (MVC) were performed by each participant where the best trial (based on peak force values) was selected for further analysis. Specifically, the participants were seated on a Universal leg extension machine and they were stabilised at the pelvis by a belt to isolate the movements to the lower extremity and avoid any assistance from the trunk muscles (hip angle = 110o, knee angle = 107o) [10]. The leg extension machine was connected to a force plate (Kistler 928B), by means of an adjustable chain. The participants were instructed to react to an auditory signal by attempting to extend their lower limbs as forcefully as possible and to maintain the maximal force for 2.5 s and after that to relax their muscles as fast as possible when the signal ceased. The force platform measured the vertical and the anterior-posterior force production and consequently the maximal isometric force (MIF) for the leg extensors was defined as the highest value of the resultant force ($F_y + F_z$) recorded during the MVC. The isometric contractions were also analysed for their force-time (f-t) curve characteristics [11] using the f-t from the level of 100 N of the MIF, up to 500 N, 1000 N, 1500 N, 2000 N and 2500 N (absolute scale) and the f-t from the level of 10% of the MIF up to 30%, 60% and 90% of the MIF (relative scale).

MAXIMAL ISOMETRIC FORCE - LEG FLEXORS

For the measurement of the MIF of the leg flexors, the participants lay prone on the leg extension machine and were stabilised at the pelvis and ipsilateral thigh (hip angle = 180o, knee angle = 140o) [12] to prevent excessive movements to the lower extremity and avoid any assistance from the back muscles. Following the same procedures as those described above, the MIF, the f-t 30%, 60%, 90%, and the f-t 250 N, 500 N, 750 N, 1000 N for the leg flexors were measured.

STATISTICAL ANALYSIS

A two-way ANOVA with repeated measures (RANOVA) was used to establish if there were any significant differences between the pre- and post-tests, the training groups and any interaction effects for each variable. For all the RANOVAs, the assumption of sphericity was tested. Given that this assumption was not violated, no adjustments were required. In the event of significant main effects, Tukey post-hoc tests were used to identify the differences. To assess the nature and strength of correlations between kinematic and kinetic variables, the Pearson's product moment correlation coefficient (r) was calculated. The significance level for all tests was set at $p < 0.05$.

RESULTS

The RANOVA showed no significant differences between the groups for all the pre-training tests. This suggests the randomisation process produced groups that are similar and therefore provides a basis for comparing uphill – downhill training against horizontal training and a control condition.

EFFECTS OF DIFFERENT TRAINING METHODS - KINEMATIC CHARACTERISTICS

The RANOVA revealed a significant interaction between groups and pre – post tests for MRS (F = 10.4; $p<0.05$). Post-hoc analysis showed that MRS increased significantly after 8 weeks of training for the U+D group by 5.9% ($p<0.05$) with all participants producing increases in their MRS (range = 0.11 - 0.88 m s^{-1}). Similarly, the RANOVA showed a significant interaction between groups and pre – post tests for step rate (F = 14.9; $p<0.05$). Post-hoc analysis revealed that step rate increased significantly for the U+D (7.4%, $p<0.05$) where all participants increased their step rate (range = 0.12 - 0.61 Hz). The RANOVA also showed significant interaction between groups and pre – post tests for contact time (F = 11.9; $p<0.05$) with the post-hoc analysis revealing that contact time decreased significantly only for U+D group (-9.5%, $p<0.05$) after the 8 weeks of training with all participants reducing their contact times (range = 4 - 20 ms). Similarly, the RANOVA showed a significant interaction between groups and pre – post tests for step time (F = 16.4; $p<0.05$). Post-hoc analysis revealed that step time decreased significantly for the U+D group (-7.9%, $p<0.05$), where all participants but one shortened their step time (range = 2 - 36 ms). Finally, the flight time showed a trend towards a decrease by an average of -6.2% (but this was not statistically significant) for the U+D group, whereas step length remained unaltered; all analysed variables did not change significantly for H and C groups (Table 1).

PROPULSIVE AND BRAKING PHASES OF CONTACT

The RANOVA showed a significant interaction effect between groups and pre – post tests for PP (F = 8.9; $p<0.05$). Post-hoc analysis revealed that PP decreased significantly by 17.0%, ($p<0.05$) for the U+D group after the 8 weeks of training (range = 3 – 20 ms), whereas for the H and C groups it did not change significantly (Table 1). There were no significant changes in the BP for all groups after the 8 weeks of training.

POSTURAL CHARACTERISTICS

There was generally a small effect on the postural characteristics for touchdown and take-off after the 8 weeks of training. The RANOVA showed a significant interaction between groups and pre – post tests for knee angle at touchdown (F = 8.9; $p<0.05$). Post-hoc analysis revealed that the U+D group showed a significant increase in the touchdown knee angle (3˚, $p<0.05$). Similarly, the RANOVA showed a significant interaction between groups and pre – post tests for and the hip angle for take-off (F = 5.6; $p<0.05$). Post-hoc analysis revealed that that the U+D group showed a significant reduction in the hip angle (3˚, $p<0.05$) for take-off after 8 weeks of training, whereas the H and C groups did not show significant changes (Table 2).

ISOMETRIC FORCE PRODUCTION CHARACTERISTICS

The RANOVA showed no significant main effects or interaction for any of the force characteristics for leg extensor muscles after 8 weeks of training for all groups (Table 3). However, it showed significant interactions between groups and pre – post tests for MIF, f-t 30%, f-t 60% and f-t 750N for leg flexors (F = 3.7, 5.2, 3.6 and 3.9, respectively; $p<0.05$). The post-hoc analysis revealed that only the U+D group ($p<0.05$) showed significant changes for MIF (7.1%; all participants produced increases, range = 20.0 – 622.4 N), f-t 30% (23.9%; all participants produced improvements, range = 2 – 24 ms), f-t 60% (25.1%; all participants produced improvements, range = 2 – 91 ms) and finally, f-t 750N (25.0%; seven participants produced improvements, range = 5 – 80 ms). The rest of the force characteristics of leg flexors of the U+D did not change significantly with training, whereas no changes in any of the examined variables for leg flexors were observed for the H and C groups (Table 4). The changes in f-t 60% correlated significantly with the changes in contact time (r = 0.56, $p<0.05$) and with the changes in the propulsive phase of contact time (r = 0.52, $p<0.05$), whereas the changes of f-t 750 N were significantly correlated with the changes in MRS (r = -0.54, $p<0.05$) and with the changes in the SR (r = -0.51, $p<0.05$).

Table 1 Mean ± s and % differences (post - pre training values) of the kinematic characteristics of all groups

	U&D			H			C		
	Pre	Post	Δ%	Pre	Post	Δ%	Pre	Post	Δ%
MRS ($m\cdot s^{-1}$)	8.26 ± 0.61	8.78 ± 0.53*	5.9	8.13 ± 0.42	8.29 ± 0.35	2.0	8.05 ± 0.99	8.02 ± 0.97	-0.3
ST (Hz)	3.99 ± 0.38	4.31 ± 0.45*	7.4	3.96 ± 0.13	4.00 ± 0.18	0.9	4.10 ± 0.20	4.09 ± 0.20	-0.2
SL (m)	2.08 ± 0.13	2.05 ± 0.15	-1.5	2.05 ± 0.07	2.08 ± 0.05	1.1	1.96 ± 0.18	1.96 ± 0.17	-0.1
CT (ms)	132 ± 16	121 ± 16*	-9.5	126 ± 11	124 ± 12	-1.6	124 ± 6	125 ± 6	0.6
FT (ms)	121 ± 16	114 ± 11	-6.2	127 ± 11	127 ± 11	0.0	121 ± 10	121 ± 12	-0.2
ST (ms)	253 ± 23	234 ± 22*	-7.9	253 ± 8	251 ± 11	-0.8	245 ± 12	245 ± 13	0.2
BP (ms)	54 ± 8	53 ± 9	-0.2	56 ± 7	55 ± 6	-1.6	57 ± 8	56 ± 9	-2.2
PP (ms)	79 ± 19	67 ± 17*	-17.0	70 ± 12	69 ± 14	-1.6	67 ± 10	69 ± 10	3.0

*Significantly different from pre-training ($p < 0.05$) as determined by repeated-measures analysis of variance and post-hoc Tukey tests. Abbreviations: U+D = combined uphill and downhill training group, H = horizontal training group, C = control group, Δ % = percentage difference between pre and post training values, MRS = maximum running speed, SR = step rate, SL = step length, CT = contact time, FT = flight time, ST = step time, BP = braking phase of contact time, PP = propulsive phase of contact time.

Table 2 Mean ± s and % differences (post – pre training values) of the posture characteristics at contact and take=off

		U+D			H			C		
		Pre	Post	Δ%	Pre	Post	Δ%	Pre	Post	Δ%
Knee (°)	Contact	149 ± 7.2	152 ± 7.3*	2.1	151 ± 6.3	149 ± 5.2	-1.4	146 ± 2.0	147 ± 3.1	0.6
	Take-off	165 ± 8.6	164 ± 9.9	-0.8	164 ± 5.5	163 ± 7.1	-0.8	164 ± 4.2	164 ± 5.3	0.5
0.5Hip (°)	Contact	134 ± 7.3	133 ± 6.1	-0.8	134 ± 5.9	138 ± 4.2	2.5	133 ± 3.7	134 ± 4.0	0.5
	Take-off	204 ± 6.9	201 ± 5.4*	-1.7	203 ± 5.2	205 ± 3.0	0.9	204 ± 4.3	204 ± 3.4	-0.2
Shank (°)	Contact	95 ± 4.5	97 ± 3.3	2.7	92 ± 4.0	92 ± 4.6	0.7	92 ± 3.5	93 ± 4.0	1.0
	Take-off	44 ± 3.8	44 ± 4.5	0.1	43 ± 3.2	43 ± 3.3	-0.2	42 ± 1.2	42 ± 1.2	1.6
Trunk (°)	Contact	80 ± 4.8	79 ± 4.0	-1.2	78 ± 3.5	78 ± 3.9	0.7	77 ± 2.8	78 ± 3.7	0.8
	Take-off	82 ± 4.1	81 ± 3.6	-1.5	84 ± 2.0	84 ± 2.2	0.1	83 ± 1.0	83 ± 1.7	-0.4
DCM (m)	Contact	0.32 ± 0.06	0.33 ± 0.03	3.0	0.30 ± 0.03	0.29 ± 0.02	-0.4	0.30 ± 0.03	0.30 ± 0.04	-0.8
	Take-off	0.57 ± 0.05	0.58 ± 0.05	2.2	0.61 ± 0.04	0.60 ± 0.04	-1.4	0.60 ± 0.05	0.59 ± 0.04	-1.7

*Significantly different from pre-training ($p < 0.05$) as determined by repeated-measures analysis of variance and post-hoc Tukey tests. Abbreviations: U+D = combined uphill and downhill training group, H = horizontal training group, C = control group, Δ % = percentage difference between pre and post training values, DCM = the distance parallel to the running surface between a line perpendicular to the running surface which passes through the centre of mass and the contact point.

Table 3 Mean ± s and % differences (post – pre training values) of the maximum isometric force and force-time characteristics expressed in relative values and absolute values of the isometric force for the leg extensor muscles of all groups

	U+D			H			C		
	Pre	Post	Δ%	Pre	Post	Δ%	Pre	Post	Δ%
MIF (N)	3246.8 ± 971.3	3320.6 ± 903.6	2.2	3109.9 ± 723.1	3155.0 ± 722.2	1.5	2910.6 ± 684.6	2904.4 ± 628.6	-0.2
f-t 30% (ms)	40 ± 15	42 ± 16	3.9	45 ± 15	48 ± 21	8.7	41 ± 14	44 ± 12	6.1
f-t 60% (ms)	79 ± 40	83 ± 42	5.0	75 ± 19	74 ± 20	-1.3	71 ± 20	73 ± 14	3.2
f-t 90% (ms)	237 ± 151	254 ± 138	6.7	154 ± 52	155 ± 45	0.2	143 ± 67	146 ± 63	1.7
f-t 500N (ms)	31 ± 14	34 ± 15	8.4	37 ± 14	39 ± 11	4.4	32 ± 9	34 ± 8	6.2
f-t 1000N (ms)	48 ± 21	53 ± 24	8.3	62 ± 25	64 ± 24	3.2	50 ± 13	54 ± 10	7.4
f-t 1500N (ms)	70 ± 40	76 ± 38	8.5	86 ± 41	91 ± 44	5.5	72 ± 20	75 ± 19	4.7
f-t 2000N (ms)	96 ± 67	104 ± 68	7.5	115 ± 66	118 ± 63	2.3	98 ± 31	103 ± 29	4.2
f-t 2500N (ms)	161 ± 160	165 ± 136	2.5	158 ± 107	162 ± 100	2.5	122 ± 36	139 ± 40	14.2

Abbreviations: U+D = combined uphill and downhill training group, H = horizontal training group, C = control group, Δ % = percentage difference between pre and post training values, MIF = maximum isometric force, f-t 30%, 60%, 90%, 500N, 1000N, 1500N, 2000N, 2500N = the time of force production from the level of 10% of the maximal isometric force up to 30%, 60%, 90%, 500N 1000N, 1500N, 2000N, 2500N, respectively.

Table 4 Mean ± s and % differences (post – pre training values) of the maximum isometric force and force-time characteristics expressed in relative values and absolute values of the isometric force for the leg flexor muscles of all groups

	U+D			H			C		
	Pre	Post	Δ%	Pre	Post	Δ%	Pre	Post	Δ%
MIF (N)	1319.6 ± 322.0	1420.6 ± 254.5*	7.1	1220.1 ± 316.6	1234.4 ± 319.0	1.2	1111.7 ± 377.6	1119.3 ± 360.7	0.7
f-t 30% (ms)	60 ± 31	48 ± 26*	-23.9	52 ± 25	46 ± 18	-12.0	51 ± 18	48 ± 16	-5.4
f-t 60% (ms)	101 ± 43	81 ± 34*	-25.1	94 ± 42	89 ± 41	-5.2	72 ± 35	75 ± 22	4.7
f-t 90% (ms)	237 ± 133	208 ± 84	-14.2	171 ± 63	165 ± 69	-3.6	160 ± 29	153 ± 27	-4.3
f-t 250N (ms)	37 ± 14	32 ± 9	-15.4	40 ± 17	39 ± 10	-3.5	33 ± 14	33 ± 10	-0.8
f-t 500N (ms)	65 ± 29	56 ± 16	-16.2	70 ± 34	73 ± 30	3.4	66 ± 30	59 ± 11	-11.2
f-t 750N (ms)	126 ± 61	101 ± 51*	-25.0	125 ± 49	119 ± 44	-4.9	85 ± 36	89 ± 35	4.1
f-t 1000N (ms)	182 ± 91	142 ± 60	-28.1	149 ± 56	153 ± 56	2.2	111 ± 36	113 ± 35	1.4

*Significantly different from pre-training (P < 0.05) as determined by repeated-measures analysis of variance and post-hoc Tukey tests. Abbreviations: U+D = combined uphill and downhill training group, H = horizontal training group, C = control group, Δ % = percentage difference between pre and post training values, MIF = maximum isometric force, f-t 30%, 60%, 90%, 250N, 500N, 750N, 1000N = the time of force production from the level of 10% of the maximal isometric force up to 30%, 60%, 90%, 250N 500N, 750N, 1000N, respectively.

DISCUSSION

EFFECTS OF DIFFERENT TRAINING METHODS

Control Group

In the present study there were no significant differences between the pre- and post-training tests for all the analysed variables in the C group, which is consistent with previous uphill-downhill studies [6, 7]. Given the consistent findings for the control group, it can be concluded that the current results were not influenced by a learning effect, which means that the familiarisation of the participants before the pre-training test was sufficient. Thus, it can be argued that any pre- to post-training changes can be attributed to the effects of the training.

Horizontal Training Group

The horizontal training method did not produce any significant increases in the analysed variables even though there were some trends of improvement in MRS (2.0%) and contact time (1.6%). Similar relative improvements for horizontal training groups were recorded in our previous uphill-downhill studies [6, 7], but on both occasions the changes were significantly lower than the ones observed for the combined training groups. In general, there is scarcity of experimental studies in the scientific literature which have employed biomechanical measurement techniques to evaluate the effectiveness of horizontal sprint training and therefore there is no opportunity to compare the current changes for the horizontal group against populations who adopted similar training programmes in the past. The limited number of scientific experimental studies is endemic to the sprint running training literature where the vast majority of the published material is rather of a coaching nature and therefore any generalizations regarding training adaptations should be treated with caution. The current study showed that traditional horizontal training tended to produce improvements in the analyzed biomechanical variables and consequently performance, but these improvements were not statistically significant. Obviously the success of the current horizontal sprint training was limited by the programme design (6 × 80m × 3 weekly sessions), yet the same volume was adopted for the uphill-downhill training programme and it produced positive performance changes. Finally, regarding the effects of the H training programme on leg strength, no significant changes were observed.

COMBINED UPHILL-DOWNHILL TRAINING GROUP

Kinematic Changes

The U+D training produced increases in MRS and step rate by 5.9% and 7.4%, respectively, whereas no changes were noted for step length. The improvement in step rate was mostly due to a reduction in step time (7.9%), which in turn is explained by the shorter contact time (9.5%). The propulsive phase was reduced (17.0%) after training, whereas the braking phase did not change significantly. The above findings may suggest an increased capacity of the leg muscles to generate force at a higher rate during the propulsive contact phase of the stride. Despite the significant changes that occurred in almost all the kinematic variables after the training period, U+D training did not generally alter the postural characteristics. The only exception was an increase in knee angle (3˚) at contact and a decrease in hip angle at takeoff by 3˚, both of which can be explained by the decrease of the propulsive phase. It can therefore be concluded that the U+D training method did not significantly alter the participants’ running posture. The current findings are comparable with those previously published [6, 7], even though the changes that observed for the U+D groups in the previous studies were slightly lower (MRS improved by 3.5% and 4.3%, step rate by 3.4% and 4.3%, contact time by 3.3% and 5.1% respectively). It is possible that the greater magnitude of change in the present study might be partly due to the longer training period (8 weeks versus 6 weeks in one of the previous studies [6]) and/or due to the approach adopted for the data analysis (the present study analysed the best trial out of the three rather than an average of the three trials). However, further work is required to substantiate the role of the training period in the magnitude of training response for the U+D method compared with horizontal sprint training. Nevertheless, it was clear from the results that U+D training produced significantly greater positive changes than H training.

Coaches believe that continuous sprint training on a horizontal surface can introduce a plateau in the maximum speed of the athlete due to the repetitive stimulus experienced during the training sessions. Therefore, maximum running sessions should incorporate a combination between resisted, assisted and horizontal runs [13]. This combination will enable athletes to run maximally under different conditions, which will result in the development of specific strength/speed parameters and also the transfer of qualities achieved during submaximal and supramaximal efforts to normal sprint running. These suggestions are supported by the findings of the present study, which showed that the combined method of training on the uphill, horizontal and downhill produced significant improvements in almost all the kinematic variable analysed.

Isometric Force Production

As proposed before, the shortened propulsive phase of the contact time could be interpreted as evidence of improved leg muscle power and may account for the improvement in running speed. In order to identify a possible cause which could account for some of the kinematic changes, the effects of training on the isometric force characteristics of the knee joint muscles were analysed. The U+D group showed significant improvements in MIF (7.1%), f-t30% (23.9%), f-t60% (25.1%) and f-t750N (25.0%) of the leg flexor muscles. The fact that the statistical analysis did not reveal significant changes for all the f-t values of the leg flexors, even though all subjects produced a consistent pattern of changes, was due to the inter-subject variation. It is clear from the data that the U+D method was beneficial for the leg flexor muscles after the eight weeks of training, whereas the horizontal method and the control condition did not lead to any significant changes. However, the U+D group showed no significant changes in the MIF and the other variables of the leg extensor muscles after the eight-week period.

Support for these findings comes from several studies; in particular, Wiemann and Tidow [14] report that during contact time in sprinting hamstring muscles supply the energy needed for the forward propulsion and, along with the *gluteus maximus* and *adductor magnus*, provide high back-swing velocity of the support leg. These suggestions are in agreement with those of Hannon et al. [15], and Wood [16] who emphasised the role of the hamstring muscle group in the sprint action and concluded that hamstring’s strength is the limiting factor in sprinting. Overall, the hamstrings play a crucial role in maximal sprinting as both leg flexors and hip extensors contribute not only to leg angular motion and energy absorbance during initial and late recovery respectively, but also as generators of forward acceleration during contact, perhaps due to the elastic energy stored in the muscles during late recovery [17, 18]. The data from the present study provided evidence of positive effects of U+D training not only on the MIF for leg flexors, which is a direct indicator of maximum leg strength, but also on the rate of force production as this was expressed by the various f-t characteristics. Furthermore, the improvements in the f-t characteristics correlated with the changes in the MRS, step rate and contact time ($p<0.05$). These correlations confirmed the proposed association between the force generation properties of the leg flexor muscles and the production of shorter contact time. As suggested previously, the shorter CT which was achieved while the stride length remained unchanged can be explained by an increased muscle power. The post-training capacity of the muscles to produce the same or greater force in a shorter period of time can influence positively the ability of the runner to generate sufficient propulsive forces at a very fast rate during the propulsive phase. This can have as a direct result an increased running speed due to an increased stride rate. The results of this study have provided support to this hypothesis.

Improvements in the rate of force production by muscles are extremely important in athletic events such sprinting where only a fraction of a second is available to develop the greatest possible force.

The fact that the strength measurements were performed under isometric conditions could be considered as a limitation since the testing setting did not resemble the movement pattern of sprint running although the sequence of intra-muscle activation would have been similar if the measurements were performed under dynamic conditions [19]. However, the above methodological limitation actually provides further support to the findings as previous research has shown that increases in strength measured under conditions other than those adopted during training underestimate the magnitude of true strength changes measured under specific to training conditions [20].

The lack of significant U+D group changes for the knee extensors' isometric force variables is quite surprising given that the role of quadriceps is also important in sprinting, especially during the late leg recovery and the initial parts of contact phase [14, 21]. In addition, it has been strongly suggested that the mechanical behaviour of the *vastus lateralis* muscle-tendon unit during the braking phase of ground contact in sprinting can increase energy storage and return during the subsequent propulsive phase [22]. Therefore, the role of the knee extensors in the adaptations related to the uphill-downhill sprint training perhaps needs re-examination in a future study.

UNDERLYING MECHANISMS AFFECTING KINEMATIC AND STRENGTH CHANGES

The positive changes in the kinematic variables together with the improvements in the isometric force variables for the leg flexors could be initially attributed to either or both hypertrophic and neural factors. A small contribution from non-hypertrophic muscular changes (e.g., changes in specific tension) cannot be ruled out as a secondary mechanism responsible for the training adaptations, but this remains only speculation since there are no data to support it [23, 24]. However, the length (8 weeks) in combination with the nature (high velocity – low resistance) of the training programme rather excludes any significant changes in muscle size as the main factor responsible for the training changes [1]. Typically, hypertrophic changes gradually dominate the spectrum of adaptations after 6-8 weeks of high resistance – low velocity training programmes [24, 25, 26]; a condition which was not employed in the current study. In addition, the two key kinematic variables showing improvements in the present study (MRS and SR) have been found to be linked directly with non-hypertrophic factors. Specifically, strong correlations have been observed between the above two kinematic variables, sprinting performance and muscle fibre distribution (% type II fibres) in elite and less skilled sprinters [27, 28].

Likewise, the significant improvements in the force-time data for the leg flexors offer support to the suggestion that the underlying mechanisms responsible for the training changes are non-hypertrophic. It is well accepted that the examination of the early parts of the force-time curve during MVCs provides an indication about the presence of training induced neural adaptations with respect to the speed of development of force levels [20, 29, 30]. Also, strong correlations have been reported previously between rate of force development values of the f-t curve and variables such as muscle fibre distribution and integrated electromyography [30-32]. More importantly Mero et al. [12] reported a positive correlation between the proportion of type II fibres and the average net ground reaction force during the propulsion phase of contact. The latter provides additional support to the suggested link between improved rate of force development during the leg flexion MVC test and the changes in the concentric contact phase observed in the present study for the U+D group.

Based on the arguments presented above, the most reasonable explanation for the kinematic and isometric force production changes for the U+D group is the involvement of training stimuli which over the period of 8 weeks created the necessary conditions for beneficial neural adaptations to occur. These neural adaptations could have mainly included an increased neural drive to the muscle and changes in the muscular coordination [20, 23, 33, 34].

The increased neural input can be the result of distinct adaptations within the nervous system or a combination of related adaptations such as the increase in the number of motor units recruited during contractions and/or an increase in the “firing” (excitation) rate of the motor units of the trained muscles [20]. Muscular coordination, which can result in changes in management between motor units of the same muscle, or a group of synergist muscles, is another key neural mechanism responsible for training specific changes. Many studies, that emphasised the principle of training specificity, demonstrated that training with high velocity movements increases high-velocity strength relatively more than low-velocity strength and vice versa [24, 35, 36]. In addition it has been shown that training at relatively high isokinetic or anisometric speeds also produces performance improvements at lower, than the training, speeds [35, 37]. This provides support to the concept that part of the positive post-training kinematic changes for the U+D group in the current study (measured during a horizontal sprint test) were associated with velocity-specific adaptations gained throughout training while sprinting downhill. It can then be argued that facilitated training, such as downhill sprinting, may instigate beneficial adaptations in the nervous system which will result in performance improvements during unaided horizontal sprinting [38].

However, uphill-downhill sprinting is not a pure facilitated training method since it incorporates additional essential stimuli. During sprinting on the platform, participants - apart from the facilitative (downhill) and normal (horizontal) stimuli - also experience a resistive stimulus (uphill) which overloads the neuromuscular system due to the extra gravitational resistance (5% of the body weight because of the 3° slope) [5]. The results of all uphill-downhill studies to date strongly suggest that the immediate transition from the overload status (uphill) to the facilitated status (downhill) yields a combined stimulus that, by repetitive application, prompts positive neuromuscular adaptations which in turn lead to improvements in the sprinting kinematics.

In terms of the location of the neuromuscular adaptations to the U+D training, it could be hypothesised that these predominantly occur in the type II motor units given that previous research has revealed strong relationships between type II fibres and sprinting performance characteristics [28, 31]. However, the possibility of this adaptation in the current uphill – downhill training study was not tested and therefore is not known.

CONCLUSION

Given the application of the randomised controlled trial, the results of the present study support the conclusion that the significant greater improvement in knee flexors’ strength, as it was expressed by the measurement of maximal isometric force and rate of force production, can be attributed to the novel U+D training method. Consistent with our previous studies, the combined uphill-downhill training was also significantly more effective in improving the maximum sprinting speed and the associated kinematic variables than an equivalent horizontal training method.

This study therefore provides original evidence regarding the internal adaptations to uphill-downhill training which consequently govern the kinematic and performance variables. The training–induced increased force generation capacity of the leg flexor muscles appears to contribute to the improvement of sprinting speed perhaps due to a more efficient muscle function during the leg-support phase of the stride. Further research is required to understand better the role of leg extensors as well as the exact nature (e.g., neural) and location of the internal adaptations, yet the current findings carry significant implications for understanding and designing sprint training programmes.

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