Original Article

The wearable devices application for evaluation of 110 meter high hurdle race

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ABSTRACT

Purpose: This study was intended to explore the continuous changes in the kinematic parameters of hurdlers in a 110 meter (110m) high hurdle race from hurdles 1 through 10. Method: Ten excellent college athletes who specialized in the 110m high hurdle race volunteered for this study. Inertial measurement units (IMUs) strapped to the back of the athlete's feet and 10 high-speed cameras were used to document the movements of the hurdlers as they were hurdling along the entire track. Kwon3D and MATLAB computer programs were employed for the analysis of kinematic parameters (take-off distance, landing distance, take-off distance percentage, landing distance percentage, flight time, time between hurdles, hurdle cycle time, hurdle cycle velocity, height of centre gravity above the hurdle and take-off angles). The trend analysis was introduced to test the changes of the parameters between hurdles. The level of significance was set to α =.05. Results: The results showed that the subjects averaged 14.31±0.29 seconds in their 110m high hurdle tests. Regarding the trend analysis, all kinematic parameters except landing distance displayed quadratic linear patterns along the 110m race. Conclusion: The athletes rapidly gained speed as they sprinted from the starting line and reached their maximum speeds between hurdles 5 and 6, after which their speed declined. In addition, the kinematic parameters changed as the running velocity varied. **Keywords:** Inertial measurement unit; Flight time; Time between hurdles; Take-off angles.

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INTRODUCTION

The 110 meter (110m) high hurdle race is one of the most exciting sprint events in track and field. The hurdler's goal is to sprint and hurdle as fast as he or she can to reach the finish line in the shortest possible time (Sidhu and Singh, 2015). From a biomechanical point of view, the hurdle race is a combination of cyclic sprinting and acyclic clearance (10 1.067m hurdles). A hurdler has to have the ability to sprint very fast; two very nimble hip joints; the ability to be explosive, maintain high speed, and stay responsive and coordinated; and good technical knowledge. Among these, the hurdle clearance technique is regarded as one of the keys to victory (Iskra and Čoh, 2011; Iskra and Walaszczyk, 2007; Čoh and Iskra, 2012; El-Hamid, 2012). In such a highly intensive athletic event, which pushes the human body to extremes, it is a daunting task to measure an athlete's techniques. With the constant evolution and innovation of measurement technology in sports science, objective analysis of the characteristic data of an athlete's continuous movements and a carefully designed training improvement program could greatly improve the athlete's performance.

Image analysis provides an objective and effective observation of athletes' techniques in the sports events they are specialized in. The hurdle race is considered one of the most technically demanding races in track and field. Hurdlers need very good horizontal speed and highly flexible hip joints to help them clear the hurdles with the lead and trail legs in the shortest possible time (Iskra and Čoh, 2011; Dapena, 1991; Kampmiller et al., 1999; Schluter et al., 1981). Several studies have analysed the hurdle clearance technique using video recording. Čoh, et al. (2000) recruited 4 members of the Slovenian national team for their study and set up 2 digital cameras at hurdle 4 to video record their clearance. The video footage was used to analyse the kinematic and dynamic parameters of the hurdle clearance. Their finding was that efficient hurdle clearance is determined by the take-off angle, the percentage between the take-off distance and landing distance, and the height of the centre of gravity (CG). Čoh and Iskra (2012) studied the hurdle clearance technique in 4 hurdlers using a 3D motion capture system and 2 cameras, and they found a direct link between the clearance height and time and the trajectory of the CG. Sidhu and Singh (2015) investigated the kinematic parameters of 2 hurdlers' hurdle clearance techniques by video recording hurdlers with 2 digital cameras next to hurdle 5. The results showed that the keys to clearing a hurdle fast and smoothly are the take-off angle, take-off distance, landing distance and height of the CG over the hurdle. It was learned from these studies that all of these kinematic parameters are the keys to smoothly clearing a hurdle.

However, current studies of hurdle clearance techniques using video analysis are subject to the range of the video recording and the time-consuming data analysis that follows. Most studies to date have been performed by video recording one or some of the hurdles. Therefore, it seems to be necessary to find a way to measure an athlete's continuous hurdling movements along the entire 110m race and to analyse the data collected in a much more time-efficient manner. In the last decade, the inertial measurement unit (IMU), equipped with an accelerometer and a gyroscope, has caught the attention of sports science for its relatively low cost, compact size, light weight and wearability. With a suitable computer program, IMUs allow for the monitoring of human movements in virtually every possible posture (Favre et al., 2009; Kuznietsov and Neubauer, 2012; McGrath et al., 2012). Mayagoitia et al. (2002) and Picerno et al. (2011) validated the high correlation between IMUs and an optical movement analysis system. The sheer number of studies with IMUs strapped to the lower limbs for measurements of walking, strides and jumps is sufficient evidence that IMUs are capable of accurately measuring the continuous movement patterns of test subjects (Picerno et al., 2011; Zhao et al., 2015; Kavanagh et al., 2006). In sports, IMUs have been widely used in measuring sports performance such as swimming, weight lifting, golf and sprints (Sato et al., 2012; Stančin and Tomažič., 2013; Göpfert et al., 2017). The studies using IMUs have produced important results.

It is clear from the above that the hurdle race, a highly complicated and physically intense track and field category, requires athletes to reach their maximum speed in the shortest possible time. It is a sport that combines a variety of sophisticated techniques, including those needed to start and run to the first hurdle, to clear the hurdles, to sprint between hurdles and to dash to the finish line. All of these movements along the entire process are just one piece of a puzzle after another for the final success. However, today's video recording technology is generally limited to how many high-speed cameras are used or how thoroughly these cameras can cover the athlete's movements. It is a challenge to video record the athlete from the starting line to the finish line. For this reason, most of the studies mentioned above were conducted with cameras pointing at one or several hurdles for video recording. One can argue that precious data may have been lost at the hurdles not covered by cameras.

With inertial measurement technology, it is possible to document the signals in a steady stream and accurately identify the movement patterns (Jensen et al., 2015; Saber-Sheikh et al., 2010). By recording the hurdle clearance of a hurdler along the entire 110m, it should be possible to observe the continuous changes in the time-distance parameters in the hurdler's hurdle clearance technique, and the data collected would be helpful for image analysis and improvement of training for both the athlete and the trainer. Given this viable alternative for measuring hurdle clearance, the data of continuous movement should provide better knowledge about the hurdle clearance technique and changes in movements. Therefore, IMUs were used to measure continuous movements in a hurdle race in conjunction with high-speed video recording at all 10 hurdles. This allowed the analysis of changes in a hurdler's clearance movements from hurdle 1 through hurdle 10 in a 110m high hurdle race.

MATERIAL AND METHODS

Experimental approach to the problem

This study was intended to investigate expert athletes' lower limb movements in a 110m high hurdle race using lightweight IMUs and high-speed cameras. The time-distance parameters measured by IMUs were combined with the kinematic parameters from image analysis for the discussion on the changes in hurdlers' movements at all 10 hurdles.

Participants

The subjects of this study were outstanding 110m hurdlers from universities. In total, 10 athletes volunteered for the study (averages of 21.5±0.50 years in age, 184.25±3.50cm in height, 75.0±5.68kg in weight and 8±2 years in training experience). All subjects attended at least 3 training sessions for the 110m hurdle technique and physical strength every week during the study and had experienced no injuries to the muscles, bones, or nerves of the lower limbs 6 months prior to the experiments. All of the subjects signed a consent form approved by the Institutional Review Board.

Measures

In this study, the kinematic parameters were referred to pervious research [Čoh and Iskra, 2012; López et al., 2018]. For the purposes of the study, ten high-speed Casio Ex F1 camera (Casio Electronics, Japan) was placed 6m to the side (the right side, from the runner's perspective) of each of the 10 hurdles at a height of 1.07m. The video recording range covered 3m before and 3m after the corresponding hurdle. A synchronizing light was placed next to each of the hurdles on the same side as the camera, and all 10 lights were synchronized with the cameras. The images were captured at 300 frames per second (300 Hz, 512 x 384 pixels) for synchronized filming. The video recordings were digitally analysed with Kwon3D (Version 3.01.017, Visol., Inc., Seoul, Korea) Motion Analysis using direct linear transformation (DLT). The human body analogue developed by Dempster (1955) was used to develop 14 limb sections and 21 joints for the calculation of kinematic parameters, including take-off distance, landing distance, take-off distance percentage, landing distance percentage, height of CG over hurdle and take-off angle (figure 1).

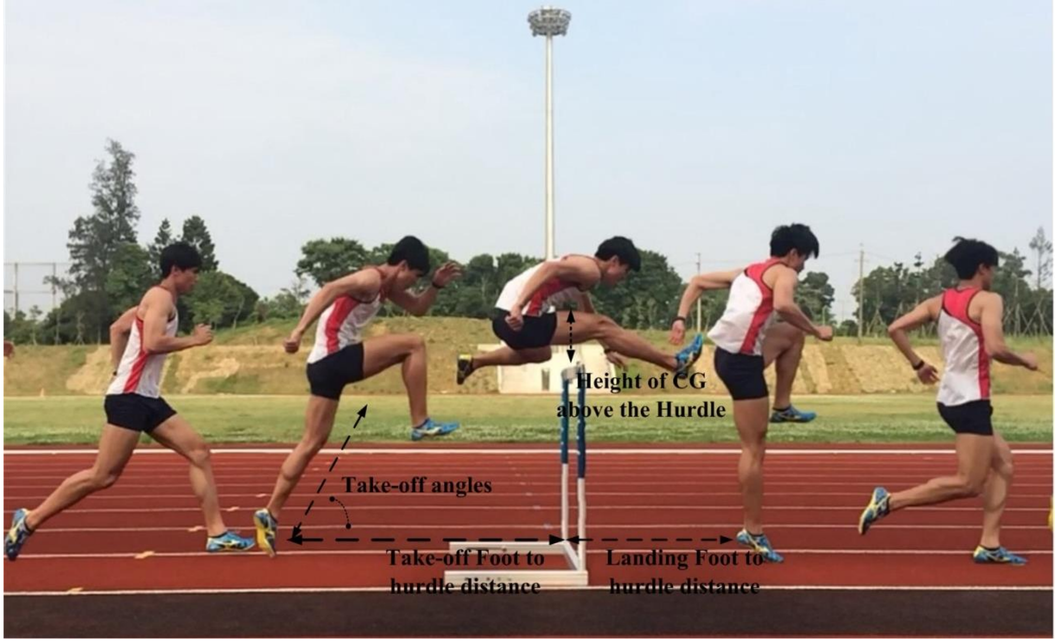

Figure 1. The Definition of Kinematic Parameters

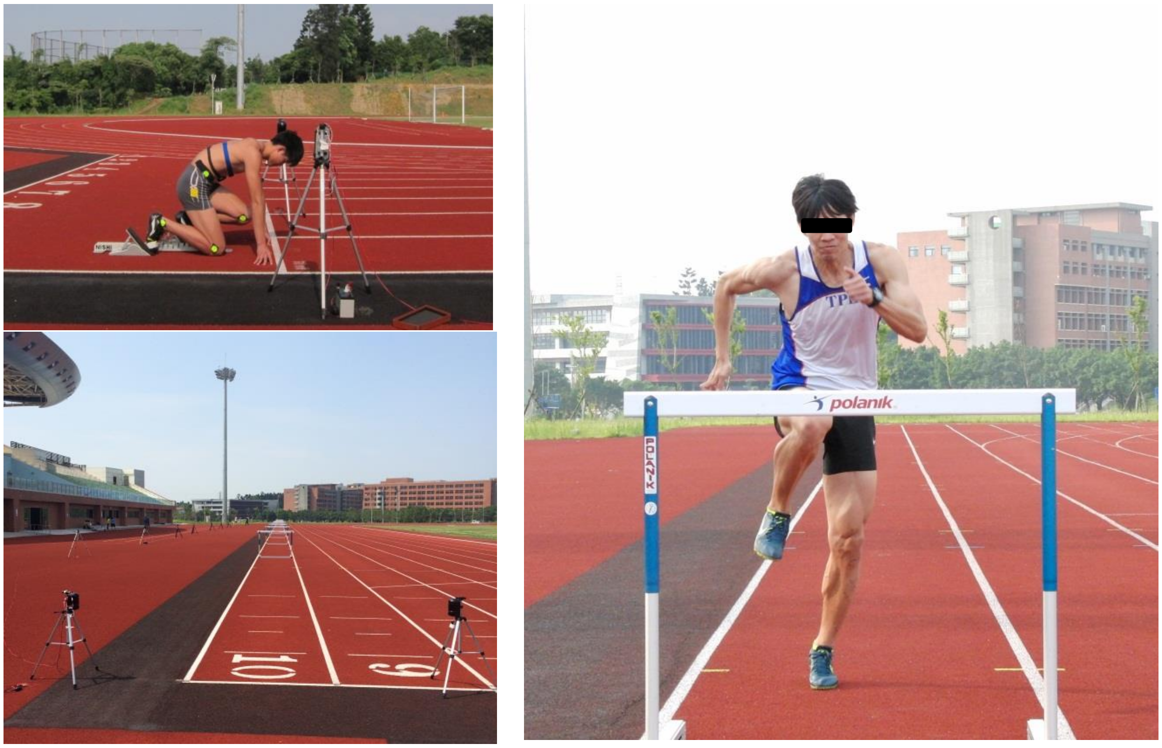
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Figure 2. Hurdle Clearance Test Setup

An IMU with an accelerometer and a gyroscope from ActiGraph GT9X Link (Actigraph LLC, Pensacola FL, USA) was used. An IMU was strapped to the dorsal surface of each foot to measure the acceleration and angular velocity of the foot in three orthogonal planes as the hurdler sprinted in a 110m hurdle test (figure 2). Weighing only 14 grams, this lightweight waterproof device was 3.5 x 3.5 x 1 cm in size. The sampling frequency was set at 100Hz. IMU data from the three axes were extracted separately. The IMU data were downloaded in raw format, gravity (g) and degrees per second (d/s). The raw signals were also digitized "by an analogue-to-digital converter and rectified and integrated over a defined epoch. Matlab (Version 7.6.0.324, MathWorks, Inc., USA) was used to develop a program for identification and analysis on the flight time, time between hurdles, hurdle cycle time and hurdle cycle velocity at each of the 10 hurdles along the 110m hurdle test.

Procedure

The normal standard Olympic hurdle was adopted for the hurdle test. Prior to the 110m high hurdle test, subjects were briefed on the instructions and safety precautions for the test procedure in order to make sure they were fully aware of the experiment steps and correct movements. The subjects started with a full-body warm-up session, just as they would in routine training, and proceeded with a full test run according to the test instructions. They were then given 3 minutes of rest after the warm-up, followed by 3 test runs for the IMU data and high-speed films. The test runs were separated by at least 15 minutes, and oral encouragement was given to the subjects to bring out their best performances as if they were actually competing.

Analyses

The statistical analysis program SPSS (version 20.0, SPSS Inc., Chicago, IL) was used to test the significance of differences. The intra-class correlation (ICC) was used to test the degree of confidence of the data collected. Descriptive statistics were used for the analysis of take-off distance, landing distance, take-off distance percentage, landing distance percentage, flight time, time between hurdles, hurdle cycle time, hurdle cycle velocity, height of CG over hurdle and take-off angle for all 10 hurdles. Trend analysis was used to test the changes in the parameters studied between hurdles. Significance was accepted $p < 0.05$.

RESULTS

The kinematic parameters of the hurdle are presented in Table 1. The average across the 10 athletes was 14.31±0.29 seconds for the 110m high hurdle race. For the further ICC correlation coefficient test, the ICC values for each of the kinematic parameters fell between 0.912 and 0.964, suggesting a very high degree of confidence. The results on take-off distance showed that the average distance was between 188.24±3.33 and 217.29±3.79 cm, accounting for 56.81±1.63 to 59.31±2.09%, respectively, of the hurdle distance. The trend analysis indicated that the result was a quadratic linear pattern ($F_{1,9}$ = 385.132, p = 0.000 and power=1.000), which increased from hurdle 1 to hurdle 5 and then descended until hurdle 10. For landing distance, the average distance was between 143.31±10.89 and 150.81±15.80 cm, accounting for 40.69±2.09 to 43.34±1.80%, respectively, of the hurdle distance. An analysis suggested no statistical significance with the result ($F_{1,9}$ = 1.763, p = 0.217 and power=0.221). For flight time, the average fell between 0.36±0.010 and 0.41±0.008 s. An analysis suggested a quadratic linear pattern ($F_{1,9}$ = 128.596, p = 0.000 and power=1.000), which increased from hurdle 1 to hurdle 5 and then decreased until hurdle 10. For time between hurdles, the average ranged from 0.69±0.005 to 2.46±0.114 s. An analysis indicated a quadratic linear pattern ($F_{1,9}$ = 2748.116, p = 0.000 and power=1.000), which decreased from hurdle 1 to hurdle 5 and then increased until hurdle 10. The flight time was the longest for hurdle 1 because the distance was 13.72m from the starting line to hurdle 1. For the hurdle cycle time, the average was between 1.05±0.01 and 2.86±0.11 s. An analysis suggested a quadratic linear pattern ($F_{1,9}$ = 2748.116, p = 0.000 and power=1.000) that fell from hurdle 1 to hurdle 5 before climbing until hurdle 10. The hurdle cycle time is the sum of the flight time and the time between hurdles, so the results were similar. For the hurdle cycle velocity, the average was 4.80±0.18 to 8.68±0.09 $m.s^{-1}$. An analysis suggested a quadratic linear pattern ($F_{1,9}$ = 13224.833, p = 0.000 and power=1.000) that increased from hurdle 1 to hurdle 6 and started to fall until hurdle 10. The hurdle cycle velocity is the hurdle cycle time divided by a fixed distance, so the results were presented as a reversed curve against the hurdle cycle time. For the height of CG over hurdle, the average ranged from 40.3±2.9 to 48.0±3.6 cm. An analysis indicated a quadratic linear pattern ($F_{1,9}$ = 23.472, p = 0.001 and power=0.990) that increased from hurdle 1 to hurdle 2, then decreased to hurdle 5 and started to increase again to hurdle 10. For the take-off angle, the average angle was 71.3±2.2 to 74.4±1.7°. An analysis indicated a quadratic linear pattern ($F_{1,9}$ = 16.650, p = 0.003 and power=0.951) that increased from hurdle 1 to hurdle 3, remained stable between hurdles 3 and 4, decreased to hurdle 5, increased steadily to hurdle 8, and remained stable again between hurdles 9 and 10.

Table 1. Kinematic and dynamic parameters of 110 m hurdling (hurdle 1-10)

	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H
Take-off Foot to hurdle distance (cm)	197.09 ±5.02	203.62 ±5.25	210.45 ±3.49	213.98 ±2.94	217.29 ±3.79	213.23 ±5.70	208.23 ±4.66	201.08 ±3.68	192.73 ±3.56	188.24 ±3.33
Landing Foot to hurdle distance (cm)	147.87 ±10.71	148.03 ±10.80	145.08 ±8.94	149.32 ±11.24	150.81 ±15.80	147.80 ±9.56	143.21 ±11.77	149.88 ±13.91	147.68 ±10.72	143.31 ±10.89
Flight time (s)	0.39 ±0.011	0.39 ±0.012	0.37 ±0.012	0.37 ±0.012	0.36 ±0.010	0.37 ±0.006	0.38 ±0.015	0.39 ±0.016	0.40 ±0.013	0.41 ±0.008
Time between hurdles (s)	2.46 ±0.114	0.73 ±0.005	0.71 ±0.004	0.70 ±0.011	0.69 ±0.005	0.68 ±0.007	0.69 ±0.008	0.71 ±0.008	0.72 ±0.012	0.73 ±0.009
Hurdle cycle time (s)	2.86 ±0.11	1.11 ±0.02	1.09 ±0.01	1.07 ±0.02	1.05 ±0.01	1.05 ±0.01	1.07 ±0.02	1.10 ±0.02	1.12 ±0.02	1.14 ±0.13
Hurdle cycle velocity ($m.s^{-1}$)	4.80 ±0.18	8.17 ±0.11	8.43 ±0.11	8.58 ±0.15	8.67 ±0.10	8.68 ±0.09	8.56 ±0.18	8.30 ±0.15	8.16 ±0.16	8.03 ±0.10
Height of CG above the hurdle (cm)	43.2 ±1.6	46.2 ±4.1	43.4 ±3.1	41.3 ±3.4	40.3 ±2.9	42.3 ±4.8	43.5 ±3.3	44.6 ±2.2	45.4 ±2.3	48.0 ±3.6
Take-off angles (degree)	73.9 ±1.2	73.5 ±2.1	73.0 ±2.2	73.3 ±2.1	71.3 ±2.2	72.9 ±1.7	73.0 ±1.0	74.4 ±1.7	73.5 ±1.8	73.8 ±1.4

DISCUSSION

The analysis of the results of the study indicated that all the kinematic parameters of the 110m high hurdle race were in a quadratic linear pattern, except for the landing distance. That is to say, the subjects started to accelerate at the starting line, reached their maximum between hurdles 5 and 6, and slowed down until hurdle 10. The change in velocity resulted in similar results in take-off distance, flight time, time between hurdles, hurdle cycle time, height of CG over hurdle and take-off angle.

A hurdle race requires extremely good techniques and kinematic intensity. Hurdlers have to reach their maximum speeds in the shortest time possible and stay in control of their techniques for starting, sprinting to the first hurdle, clearing the hurdles, sprinting between hurdles, and making the final sprint. The details in every step along the process are one of the keys to victory in a hurdle race. Therefore, when approaching a hurdle, the lead leg has to be extended completely and lifted as high as possible, the knee has to be higher than the waist, and the torso has to lean forward rapidly. At this stage of the race, the knee flexors in the lead leg and the hip flexors in the trail leg must be highly flexible. The lead leg has to thrust down very hard when clearing the hurdle in order to prevent excessive lifting of the body and thus excessive flight time. The CG of the body has to be kept from moving up and down too much during a hurdle clearance. For this, the hurdler has to keep the CG at a proper height in order to reduce the loss of horizontal speed for faster clearance.

However, these technical details vary from athlete to athlete, since the proportions of body height and weight vary from person to person. The athlete's physical proportions influence the proportions of the clearance techniques, such as stride distance, take-off distance, take-off angle, lead leg angle, height of CG over hurdle and landing distance. These kinematic parameters are the keys to smooth hurdle clearance techniques along the 110m. The mastery of coordination techniques helps to reduce the flight time, and body coordination and the maintenance of rhythm in sprinting between hurdles are some of the elements of success. The well-balanced combination of physical qualities such as explosiveness, muscle strength and endurance is what takes an athlete to the next level of performance.

It was found from the results that for the 110m high hurdle race, the average take-off distance % was 58.16%, and the average landing distance % was 41.84%. These values are different from the 65% for take-off distance and 35% for landing distance proposed previously in several studies (Kampmiller et al., 1999). Previous studies reported that the technique proportion of the take-off distance was based on horizontal velocity and body characteristics (height and weight) (Iskra and Walaszczyk, 2007), and the take-off distance varied due to differences in the physiques of athletes. Therefore, it is difficult to compare the percentages in this study with the 65% for take-off distance and 35% for landing distance previously reported. When it comes to the take-off and landing distances during a hurdle clearance, any hurdler, regardless of physique, has to clear hurdles of the same 1.067m height. Once over a hurdle, the athlete is subject to the force of gravity. The principle of the parabola indicates that the highest point of the CG during the hurdle clearance should be directly above the hurdle, suggesting that the kinematic and dynamic structures of take-off and landing points have direct influences on the velocity of hurdle clearance (Schluter., 1981). Therefore, it was evident in the results that the changes in take-off distance influenced the total length of hurdle clearance and thus the highest point of the CG above the hurdle during clearance and other relevant kinematic parameters.

The kinematic parameters of hurdling obtained in this study are similar to those from the hurdle clearance technique studies conducted by Čoh and Iskra (2012); Sidhu and Singh (2015); Čoh et al. (2000); and Bubanj et al. (2008). The hurdle clearance technique varies from subject to subject due to differences in body proportions and other physical elements, with corresponding differences in study results. The hurdle clearance time is more or less dependent on the proportion of the take-off angle when clearing a hurdle, the take-off distance, landing distance, total length of hurdle clearance and the height of CG at clearance. These elements determine the time for hurdle clearance. Consequently, it would not be appropriate to apply a universal set of kinematic parameters to an outstanding athlete. The differences in physique and physical qualities prevent identical performances in multiple athletes. It is prudent to shorten the clearance time and improve an athlete's performance with strategy and the application of proven techniques based on individual advantages in physique and physical qualities. In addition, this gait analysis equipment were effective to determine the stride characteristics and long-term monitor in the field.

CONCLUSIONS

The techniques of the 110m high hurdle race vary from athlete to athlete. Differences in body characteristics (height and weight) and physique (explosiveness, muscle strength and flexibility) determine the proportion of hurdle clearance techniques. A taller hurdler should have a lower take-off angle. A take-off distance of 2.00 to 2.20m should result in a rather flat parabolic trajectory during clearance and relatively lower height of CG over the hurdle. With these parameters, the landing distance of the trail leg after clearance should fall between 1.30 and 1.45m, which would reduce the flight time and horizontal energy loss, and thus clearance time. On the other hand, a shorter athlete should have a faster horizontal speed to make up for differences in physique. For such an athlete, the hurdle clearing movements are highly complicated, requiring a faster horizontal speed along with continuity and coordination of movements in order to achieve the optimized hurdle clearance technique. It is clear that 110m hurdlers should find the hurdle clearance techniques that best fit their physiques in order to achieve fast and smooth hurdle clearance and therefore shorter clearance time. In conclusion, the presented results provide a quantified insight for the expert athletes. It is a suitable tool to analyse running features and enables feedback intervention applications in the training progress.

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REFERENCES

Čoh, M., & Iskra, J. (2012). Biomechanical studies of 110 m hurdle clearance technique. Sport Science, 5(1), 10-14.

Coh, M., Jost, B., & Skof, B. (2000). Kinematic and dynamic analysis of hurdle clearance technique. In ISBS-Conference Proceedings Archive (Vol. 1, No. 1).

Dapena, J. (1991). Hurdle clearance technique. Track and Field. Quart. Rev.116 (3), 710- 712.

Dempster, W. T. (1955). Space requirements of the seated operator, geometrical, kinematic, and mechanical aspects of the body with special reference to the limbs. Michigan State Univ East Lansing. https://doi.org/10.21236/AD0087892

El-Hamid, M. G. (2012). Effect of Training by Using the Change in the Official Measurements on Some Special Variables and Record Level of 110m Hurdles Competitors. World Journal of Sport Sciences, 6(2), 152-156.

Favre, J., Aissaoui, R., Jolles, B. M., de Guise, J. A., & Aminian, K. (2009). Functional calibration procedure for 3D knee joint angle description using inertial sensors. Journal of biomechanics, 42(14), 2330-2335. https://doi.org/10.1016/j.jbiomech.2009.06.025

Göpfert, C., Pohjola, M. V., Linnamo, V., Ohtonen, O., Rapp, W., & Lindinger, S. J. (2017). Forward acceleration of the centre of mass during ski skating calculated from force and motion capture data. Sports Engineering, 20(2), 141-153. https://doi.org/10.1007/s12283-016-0223-9

Iskra, J., & Coh, M. (2011). Biomechanical studies on running the 400 m hurdles. Human Movement, 12(4), 315-323. https://doi.org/10.2478/v10038-011-0035-5

Iskra, J., & Wlaszczyk, A. (2007). Types of strides pattern and time distribution in elite 400-m-hurdlers.

Jensen, U., Schmidt, M., Hennig, M., Dassler, F. A., Jaitner, T., & Eskofier, B. M. (2015). An IMU-based mobile system for golf putt analysis. Sports Engineering, 18(2), 123-133. https://doi.org/10.1007/s12283-015-0171-9

Kampmiller, T., Slamka, M., & Vanderka, M. (1999). Comparative biomechanical analysis of 110 m hurdles of Igor Kovač and Peter Nedelicky. Kinesiologia Slovenica, 5(1-2), 26-30.

Kavanagh, J. J., Morrison, S., James, D. A., & Barrett, R. (2006). Reliability of segmental accelerations measured using a new wireless gait analysis system. Journal of biomechanics, 39(15), 2863-2872. https://doi.org/10.1016/j.jbiomech.2005.09.012

Kuznietsov, A., & Neubauer, D. (2012, March). A wireless framework for movement activity monitoring of sprinters. In Proceedings of the 9th International Multi-Conference on Systems, Signals and Devices, Chemnitz, Germany (pp. 20-23). https://doi.org/10.1109/SSD.2012.6198028

López del Amo, J. L., Rodríguez, M. C., Hill, D. W., & González, J. E. (2018). Analysis of the start to the first hurdle in 110 m hurdles at the IAAF World Athletics Championships Beijing 2015.

McGrath, D., Greene, B. R., O'Donovan, K. J., & Caulfield, B. (2012). Gyroscope-based assessment of temporal gait parameters during treadmill walking and running. Sports Engineering, 15(4), 207-213. https://doi.org/10.1007/s12283-012-0093-8

Mayagoitia, R. E., Nene, A. V., & Veltink, P. H. (2002). Accelerometer and rate gyroscope measurement of kinematics: an inexpensive alternative to optical motion analysis systems. Journal of biomechanics, 35(4), 537-542. https://doi.org/10.1016/S0021-9290(01)00231-7

Picerno, P., Camomilla, V., & Capranica, L. (2011). Countermovement jump performance assessment using a wearable 3D inertial measurement unit. Journal of sports sciences, 29(2), 139-146. https://doi.org/10.1080/02640414.2010.523089

Radoslav, B., Saša, B., Darko, M., Vladan, P., Aleksandar, R., & Ratko, S. (2008). Comparative biomechanical analysis of hurdle clearance techniques on 110 m running with hurdles of elite and non-elite athletes. Serbian Journal of Sports Sciences, 2, 37-44.

Sato, K., Sands, W. A., & Stone, M. H. (2012). The reliability of accelerometry to measure weightlifting performance. Sports Biomechanics, 11(4), 524-531. https://doi.org/10.1080/14763141.2012.724703

Saber-Sheikh, K., Bryant, E. C., Glazzard, C., Hamel, A., & Lee, R. Y. (2010). Feasibility of using inertial sensors to assess human movement. Manual Therapy, 15(1), 122-125. https://doi.org/10.1016/j.math.2009.05.009

Schluter, W. (1981). Kinematische Merkmale der 110-m Hurdentechnik. Leistungssport, 2, 118-127.

Sidhu, A. S. & Singh, M. (2015). Kinematical analysis of hurdle clearance technique in 110m hurdle race. International Journal of Behavioural Social and Movement Science, 4(2), 28-35.

Stančin, S., & Tomažič, S. (2013). Early improper motion detection in golf swings using wearable motion sensors: The first approach. Sensors, 13(6), 7505-7521. https://doi.org/10.3390/s130607505

Tien, I., Glaser, S. D., Bajcsy, R., Goodin, D. S., & Aminoff, M. J. (2010). Results of using a wireless inertial measuring system to quantify gait motions in control subjects. IEEE Transactions on Information Technology in Biomedicine, 14(4), 904-915. https://doi.org/10.1109/TITB.2009.2021650

Zhao, Y., Gerhard, D., & Barden, J. (2015). Periodicity-based swimming performance feature extraction and parameter estimation. Sports Engineering, 18(3), 177-189. https://doi.org/10.1007/s12283-015-0178-2