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Ground Reaction Forces Through a Range of Speeds in Steeplechase Hurdling

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Master of Science

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ABSTRACT

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The men's steeplechase event requires participants to jump over thirty-five 0.914-meter-tall obstacles, 4 rigid barriers and 1 fixed barrier followed by a 3.66-meter-long water pit per lap, over a 3000-meter distance. This study investigated the effect of increasing running velocity, through a range of 5.33 m/s to 6.66 m/s, on takeoff and landing ground reaction forces, for males during steeplechase hurdling using a force plate embedded under a track surface. Subjects completed 1 trial within each of 6 different pace ranges in a random order, once with a hurdle following the force plate to measure the takeoff ground reaction forces and a second time with the hurdle prior to the force plate to measure the landing ground reaction forces. Within a repeated measures linear mixed model during takeoff, peak vertical force ($r^2 = 0.1968$, $p < 0.01$) and horizontal propulsive impulse ($r^2 = 0.0287$, $p = 0.02$) were positively correlated with increasing velocity, and ground time ($r^2 = 0.1904$, $p < 0.01$) was negatively correlated with increasing velocity. Within a repeated measures linear mixed model during landing, vertical impact force loading rate ($r^2 = 0.0099$, $p < 0.01$) was positively correlated with increasing velocity and ground time ($r^2 = 0.2889$, $p < 0.01$), vertical impulse ($r^2 = 0.1704$, $p = 0.02$), and horizontal braking impulse ($r^2 = 0.0004$, $p = 0.05$) were negatively correlated with increasing velocity. As male steeplechasers prepared to hurdle at increasing speeds, they produced a greater peak vertical force on the takeoff step while decreasing the ground time during takeoff, and increasing the horizontal propulsive impulse to carry themselves beyond the hurdle. While landing from the hurdle at increasing speeds, the athlete decreased the amount of time spent on the landing stance and the vertical impulse, and increased the magnitude of horizontal braking impulse and vertical loading rate. The relationships of these variables: takeoff peak vertical force, takeoff ground time, takeoff horizontal impulse, landing ground time, and landing vertical loading rate to increasing velocity were all comparable to overground running responses. The data differed from running by not indicating any change in hurdling takeoff horizontal braking impulse; however, the horizontal braking impulse did increase on hurdling landing. It was expected to decrease on hurdling landing due to the foot landing more underneath the center of mass after hurdling compared to running. The decrease in landing vertical impulse as speed increased also differed from normal running steps. We suggest that further research include kinematic measures to better understand the relationship between these variables as hurdling velocity increases.

Keywords: steeplechase, ground reaction force, hurdling, track

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1. Introduction

Questions about the limits of human physical performance have led to competitive events throughout history. Over time, a unique event developed in track and field called the steeplechase (Figure 1). The men's event requires participants to jump over thirty-five 0.914-meter-tall obstacles, 4 rigid barriers and 1 fixed barrier followed by a 3.66-meter-long water pit (Figure 2) per lap, over a 3000-meter distance.[1] It is an event competed throughout the United States and internationally at Junior (under age 19) and Senior levels.

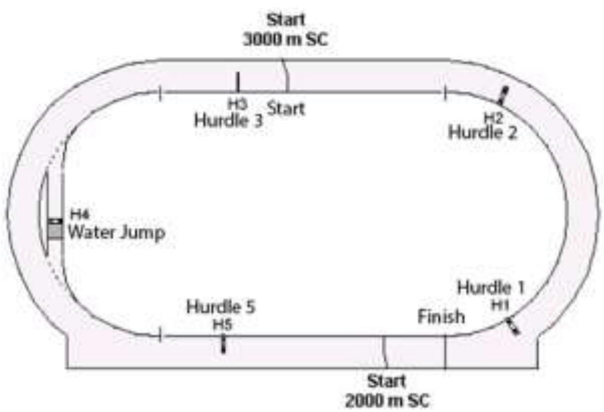

Figure 1-Steeplechase Track Setup (courtesy of German Federation). The steeplechase is a 3000-meter event approximately 7.5 laps long. The event involves 4 hurdles and 1 water jump per lap starting with hurdle 1.

Most of the knowledge about steeplechase has come from relatively subjective coaching strategies; e.g., emphasis concerning specific racing skills, need for flexibility, coordination, and fearlessness.[2,3,4,5,6,7,8] Only a few peer-reviewed scientific articles exist specific to the steeplechase; 1 investigating the energetic cost of steeplechase hurdling,[9] a few identifying kinematics,[10,11,12,13] and 1 investigating kinetics.[14] A related study on track hurdling compared steeplechase hurdling to sprint hurdling mechanics,[15] while other studies focused entirely on sprint hurdling.[16,17,18,19,20,21] Some related studies that have focused on obstacle navigation outside of track and field performance have investigated running mechanics during the approach and clearance of obstacles[22,23] and changes in running foot strikes as obstacle heights change.[24]

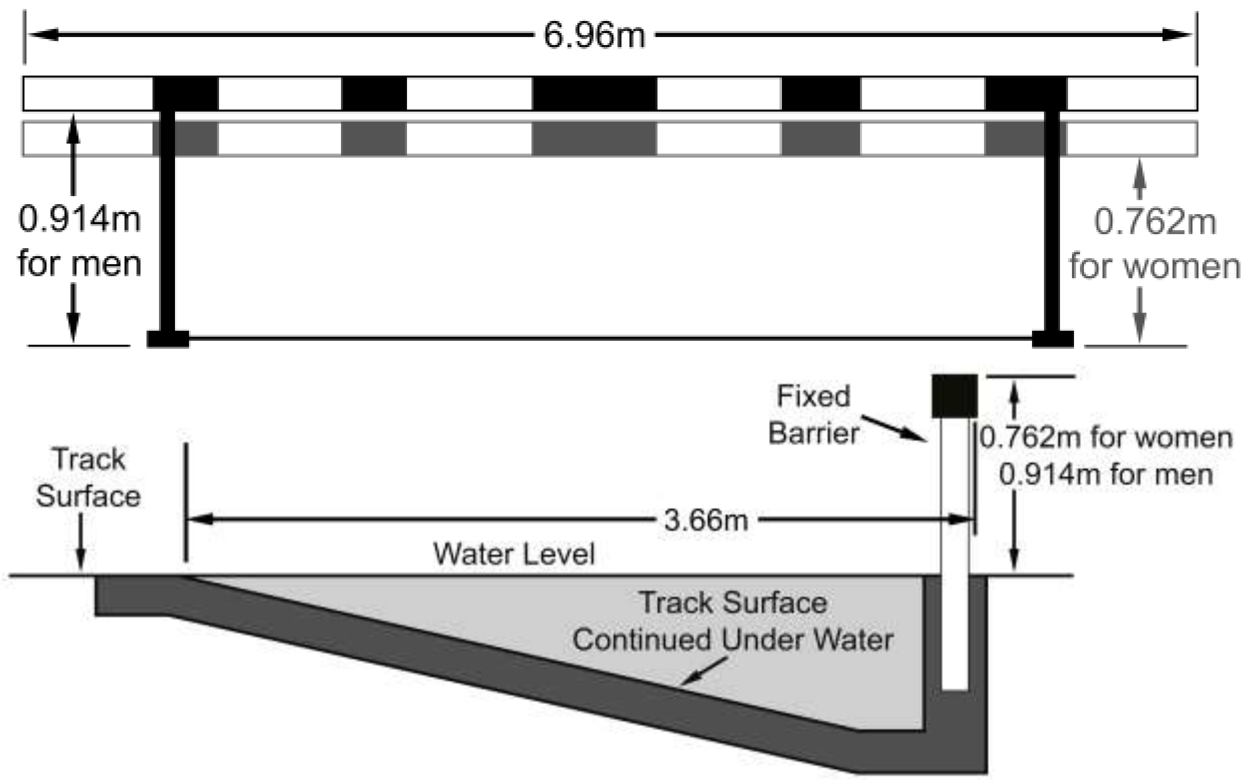

Figure 2-Steeplechase Hurdle and Steeplechase Water Jump (from German Federation). Obstacles are 0.914-meter tall for men and 0.762-meter tall for women. The hurdles are rigid allowing for little to no movement and the water jump is fixed in place.

After the women's steeplechase event was first competed during the 2005 World Championships, Hunter compared men and women steeplechasers and showed that, relative to men, women's horizontal velocity decreased less during hurdling most likely due to the lower barrier heights while hurdling (0.914-meter for the men and 0.762-meter for the women).[1,11] However, the women's horizontal velocity slowed more than the men's during the water jump obstacle.[12] Studying the effect of hurdling on oxygen consumption, Earl found that hurdling requires a greater $\dot{V}O_2$ response compared to open running by 2.6%, but that accelerating during the hurdle approach assists in maintaining horizontal velocity while not requiring a significant increase in energy expenditure.[9] Another study that analyzed kinematic variables of steeplechase performance identified that the faster and slower male race groups were significantly different for hurdling variables such as obstacle pace, and flight distance; and for the water jump variables significant differences were found for obstacle pace and loss of velocity. The faster athletes navigated the obstacles more quickly and lost a smaller percentage of their velocity due to the obstacle.[13] This information provided potential sources for improving steeplechase performance.

Several research studies focused on the ground reaction forces in running found that as speed increased the peak vertical ground reaction force increased, and as the peak vertical ground reaction force increased the ground time decreased.[25,26,27] Most recently, researchers comparing open running ground reaction forces to steeplechase hurdling and water jump ground reaction forces found significantly higher vertical ground reaction forces on the body during takeoff and landing of steeplechase hurdle and water jump navigation compared to open running at a fixed pace.[14] The effect that changes in pace will have on the ground reaction forces from steeplechase hurdling is not yet known.

This study describes how the takeoff and landing ground reaction forces for male Division I collegiate level steeplechasers change with increasing pace. It was hypothesized that increases in pace would correspond with increases in peak vertical force, vertical impact force loading rate, vertical impulse, and horizontal propulsive impulse, and decreases in horizontal braking impulse and ground time during hurdle takeoff and landing. The ground reaction force measurements from this study, other studies, and future research could help provide coaches and athletes with the knowledge needed to design training protocols that will assist steeplechasers to safely experience ground reaction forces during the steeplechase through sport specific plyometric or resistance training programs. The data collected during this study might also serve as a model, a representation of ground reaction force for high-level steeplechasers performing at high speeds.

2. Material and Methods

2.1 Participants

Pilot data analysis of the peak vertical ground reaction force provided estimates of measurement variability and expected differences from slowest to fastest speeds. These pilot data indicated that 12 subjects were needed to produce a power of 0.80 with alpha set at 0.05. Subjects were current or former (having competed in the last 2 years) NCAA Division I male steeplechase athletes recruited through personal correspondence and word of mouth to participate in this study (Table 1). Subjects ranged from personal best times of 8:36 to 9:39. Written informed consent was obtained for each participant prior to participation in the study, and the university institutional review board approved the protocol prior to data collection.

Table 1 – Subject Descriptives

Age (years)	Height (m)	Mass (kg)	Left Leg Length (m)	Right Leg Length (m)	Personal Best (min:ss)	Number of Seasons	Career Races
23 ± 2	1.79 ± 0.04	68.7 ± 4.3	0.93 ± 0.04	0.93 ± 0.04	8:59.5 ± 18.6	2.2 ±1.3	7.6 ± 5.9

Mean ± standard deviation. Twelve subjects were used who were current or former (having competed in the last 2 years) NCAA Division I male steeplechase athletes.

2.2 Procedures

This study was a cross sectional design collecting ground reaction forces at different running velocities for subjects in 1 session. Takeoff and landing trials were completed separately. Each trial measured either the ground reaction forces during the takeoff step of a hurdle motion or the landing step of a hurdle motion, but not both, because there was not access to a location with the capability to measure both the takeoff and landing of a single jump. Each trial velocity and takeoff or landing measurement was collected in a random order for each subject.

Subjects were recruited as outlined above and scheduled for a data collection session lasting approximately 60 minutes. Subjects reported to the indoor track facility where a force plate was embedded under the track surface. At the beginning of a session, subjects were presented with the informed consent form and given time to read and understand the form. After written consent was given, the subjects filled out the subject information sheet and then began the warm-up procedure. In addition to reporting his name, date, age, height, and weight, the subject added his personal best time, the number of steeplechase seasons in which he had competed, the number of steeplechase races in which he had competed, and his preferred lead leg.

Subjects were allowed to warm-up at a self-selected pace around the indoor track for one-half mile. Following the running warm-up, subjects performed a hurdle warm-up beginning with wall drills and then over hurdle drills familiar to steeplechase athletes. Each drill was demonstrated before the subjects were asked to complete the drill.

The wall drills had 2 parts: lead leg drills and trail leg drills. The lead leg drills placed a hurdle (UCS Spirit, NV, USA) against a wall at the men's barrier height of 36 inches and subjects performed a walking approach to the hurdle before extending the lead leg up and over the hurdle until the leg touched the wall over the hurdle simulating the lead leg motion of a hurdle. The subjects then backed up and repeated the procedure. The trail leg drills moved the hurdle 1 hurdle length from the wall allowing the subjects to stand next to the hurdle and lean forward to place both hands on the wall. The subjects lifted their hurdle side leg up and over the hurdle simulating the trail leg motion of the hurdle. The subjects then brought the leg back to the hurdle and repeated the procedure. In summary, the wall drills consisted of 5 lead leg drills for each leg and were followed by 5 trail leg drills for each leg.

A hurdle was placed near the force plate where the data collection occurred. The placement of the hurdle was adjusted for each subject's preference and trial speed to ensure that the subject landed on the force plate. The subjects then changed into steeplechase racing shoes and practiced 2 or 3 running approaches with the hurdle positioned with the force plate to finish the warm up procedure. During the running approaches, the starting location was identified to assist the subjects in approaching the hurdle without breaking stride during the data collection. With the subject's warm-up completed, he was then prepared to begin the data collection portion of the testing procedure.

The trial order for each subject was initially determined through a random order generation. Each subject then attempted to follow the given order; however, to avoid risk of injury from fatigue due to excessive hurdling, a trial was counted whether or not it was at the correct pace if that pace had not yet been completed. The subject then attempted to continue the generated order again while still allowing for pacing mistakes. The pace ranged from a 4:00-minute pace to a 5:00-minute pace per 1600 meters and was divided into six 10-second intervals resulting in pace ranges of 4:00–4:10, 4:10–4:20, 4:20–4:30, 4:30–4:40, 4:40–4:50, and 4:50–5:00. Successful trials within each pace range were measured for both a takeoff and a landing. These velocities included the range of elite steeplechasers' finishing velocities to collegiate steeplechasers' slower lap velocities representing the realistic paces seen during a steeplechase competition (Table 2). A trial did not count if the hurdle was hit during navigation or the wrong leg was used as the lead leg. A total of 3 attempts (among 3 subjects) were excluded due to hitting the hurdle and 22 attempts (among 8 subjects) were excluded due to leading with the wrong leg. An average of 24.3 ± 3.1 attempts was needed per subject to complete the 6 takeoff measures and the 6 landing measures. No subject completed the trials in the same order. Six subjects completed the trials beginning with the takeoff measures and six subjects beginning with the landing measures.

Table 2 – Pace Range Information for Collection Setup

Time per 1600m (min:s)	Time per 400m (s)	3000m Steeplechase Time (min:s)	Velocity (m/s)	20 Meter Time (s)
4:00	60.0	7:30	6.66	3.00
4:10	62.5	7:49	6.40	3.13
4:20	65.0	8:07	6.15	3.25
4:30	67.5	8:26	5.93	3.37
4:40	70.0	8:45	5.71	3.50
4:50	72.5	9:04	5.52	3.62
5:00	75.0	9:23	5.33	3.75

Pace ranged from 4:00 pace to 5:00 pace, per 1600 meters, and was divided into six 10 second intervals resulting in pace ranges of 4:00–4:10, 4:10–4:20, 4:20–4:30, 4:30–4:40, 4:40–4:50, and 4:50–5:00. These velocities included the range of the elite steeplechaser's finishing velocities to the collegiate steeplechaser's slower lap velocities representing the realistic paces seen during a steeplechase competition.

Timing lights (Brower Timing Systems, UT, USA) were placed 20-meters apart with the first 10-meters occurring prior to the end of force plate and the second 10-meters following the force plate to calculate the velocity of the trial (Figure 3). Trials were categorized using the 20-meter time ranges reported in Table 2.

This study utilized a 60cm by 90cm Bertec force plate (Bertec Corporation, OH, USA) mounted into the surface of an indoor track collecting at 1000 Hz to measure the takeoff and landing ground reaction forces. A hurdle (UCS Spirit, NV, USA) set at 0.914m tall was placed after the force plate to measure the ground reaction forces for hurdling takeoff and before the force plate to measure the ground reaction forces for hurdling landing. A cone was placed 5-meters beyond the second set of timing lights as a finishing point to assist the subject in maintaining his velocity through the entire timing zone (Figure 3).

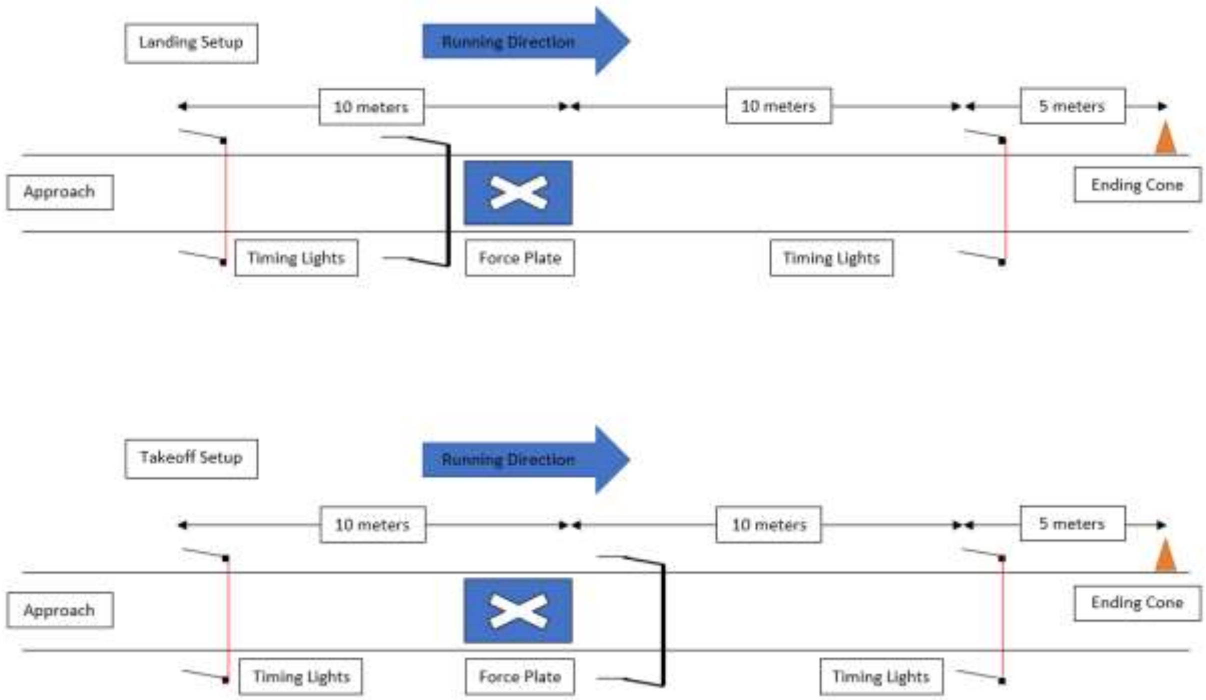

Figure 3-Data Collection Setup. Subjects accelerated during the approach before passing through the first set of timing lights 10-meters prior to the force plate. Subjects cleared the hurdle onto the force plate to measure landing ground reaction force and off the force plate to measure takeoff ground reaction force. Subjects attempted to maintain an even pace throughout the timing zone aided by a cone acting as a finishing mark 5-meters beyond the second set of timing lights. Trial pace was determined by the 20-meter time.

A Sony Alpha a7S II Mirrorless Digital Camera (Sony Corporation, Tokyo, Japan) was placed facing perpendicular to the running direction capturing a sagittal plane view. The camera collected at 120 Hz to confirm foot placement on the force plate.

Force data were filtered using a fourth order 50 Hz low-pass zero-lag Butterworth filter. After processing the data, peak vertical force (PVF), vertical impact force loading rate (VLR), vertical impulse (VIM), horizontal braking impulse (HBI), horizontal propulsive impulse (HPI), change in velocity (CIV), and ground time (GT) were calculated using a custom macro in Visual Basic for Applications (Microsoft Corp, Seattle, WA). The point preceding a threshold of greater than 10 N for foot strike and the first point less than 5 N for toe off was used to calculate GT.

2.3 Statistical Analysis

A repeated measures linear mixed model analysis was run using SAS (IBM Corp, Cary, TX) with the dependent variables versus running velocity. This determined the relationship between the ground reaction force variables and velocity. Alpha was set at 0.05. The repeated measures linear mixed model analysis predicts the velocities based upon the dependent variables. Within-subject correlations existed within our data set. The mixed model provides us with a method to predict these correlations in order to produce better estimates of the independent fixed effects.[28]

3. Results

3.1 Takeoff Ground Reaction Forces

Descriptive statistics for the takeoff variables in each pace range are listed in Table 3. PVF ($r^2 = 0.1968$, $p < 0.01$) and HPI ($r^2 = 0.0287$, $p = 0.02$) were positively correlated with velocity, while GT ($r^2 = 0.1904$, $p < 0.01$) was negatively correlated with velocity (Figure 4).

Table 3 – Takeoff Variable Descriptive Data

Variable	4:00–4:10	4:10–4:20	4:20–4:30	4:30–4:40	4:40–4:50	4:50–5:00
Velocity (m/s)	6.53 ± 0.07	6.25 ± 0.08	6.05 ± 0.08	5.80 ± 0.06	5.62 ± 0.07	5.44 ± 0.04
PVF** (BW)	6.1 ± 1.2	6.0 ± 0.8	5.7 ± 0.8	5.4 ± 0.9	4.9 ± 0.8	4.8 ± 1.0
GT** (s)	0.158 ± 0.007	0.165 ± 0.011	0.164 ± 0.011	0.172 ± 0.013	0.172 ± 0.013	0.174 ± 0.011
VIM (BWs)	0.415 ± 0.023	0.417 ± 0.016	0.418 ± 0.018	0.429 ± 0.026	0.428 ± 0.021	0.425 ± 0.022
HBI (BWs)	-0.074 ± 0.026	-0.070 ± 0.023	-0.075 ± 0.026	-0.079 ± 0.022	-0.076 ± 0.026	-0.074 ± 0.022
HPI** (BWs)	0.034 ± 0.010	0.032 ± 0.009	0.033 ± 0.015	0.031 ± 0.011	0.031 ± 0.010	0.029 ± 0.010
CIV (m/s)	-0.40 ± 0.27	-0.37 ± 0.23	-0.41 ± 0.35	-0.47 ± 0.19	-0.44 ± 0.28	-0.45 ± 0.23
VLR (BW/s)	340.9 ± 113.1	327.0 ± 81.3	328.7 ± 83.5	315.8 ± 64.3	292.8 ± 82.8	276.4 ± 89.2

Mean ± standard deviation. **Indicates statistically significant variables with increasing velocity. PVF ($r^2 = 0.1968$, $p < 0.01$) and HPI ($r^2 = 0.0287$, $p = 0.02$) were positively correlated with increasing velocity, while GT ($r^2 = 0.1904$, $p < 0.01$) was negatively correlated with increasing velocity.

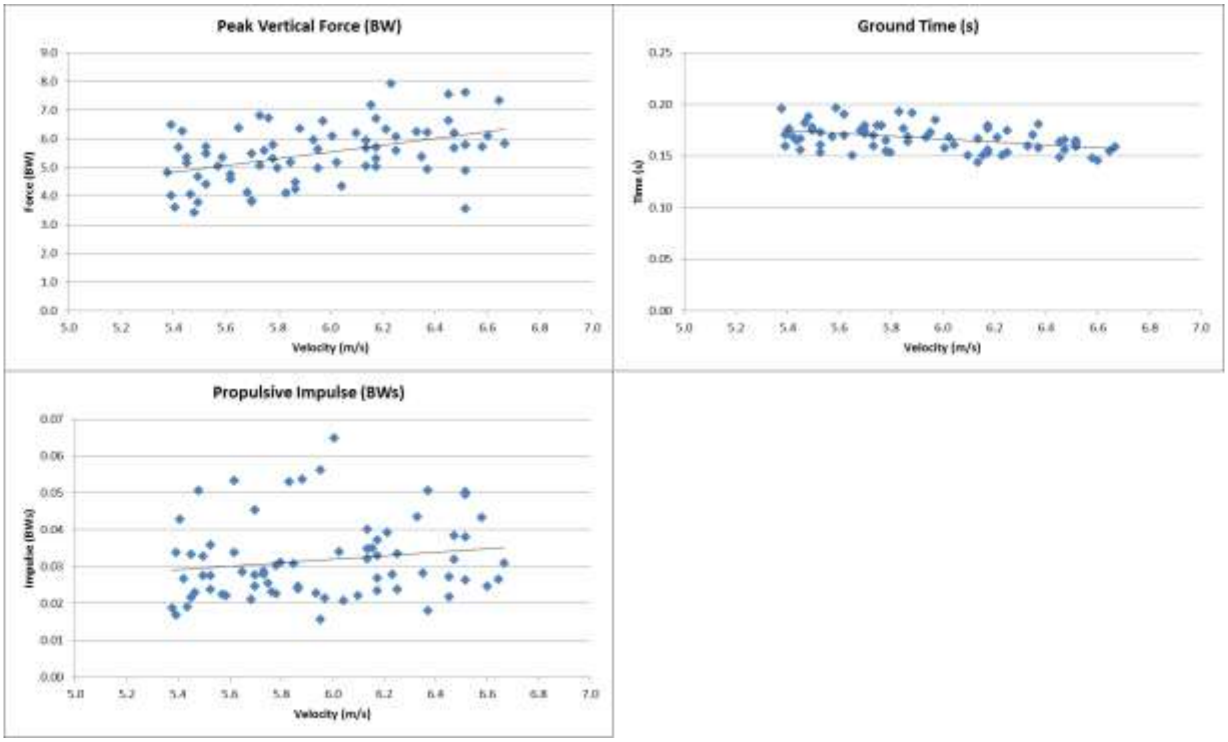

Figure 4-Takeoff Variable Scatterplots. Individual scatterplots for statistically significant variables correlated with increasing velocity. PVF ($r^2 = 0.1968$, $p < 0.01$) and HPI ($r^2 = 0.0287$, $p = 0.02$) were positively correlated with increasing velocity, while GT ($r^2 = 0.1904$, $p < 0.01$) was negatively correlated with increasing velocity.

3.2 Landing Ground Reaction Forces

Descriptive statistics for the landing variables in each pace range are listed in Table 4. GT ($r^2 = 0.2889$, $p < 0.01$), VIM ($r^2 = 0.1704$, $p = 0.02$), and HBI ($r^2 = 0.0004$, $p = 0.05$) were each negatively correlated with velocity, while VLR ($r^2 = 0.0099$, $p < 0.01$) was positively correlated with velocity (Figure 5).

All subjects were able to complete a successful takeoff and landing trial within each pace range resulting in no missing data points for any subject. The assumptions for a repeated measured linear mixed model analysis are similar to those of linear regression, but we assume additional within-subject covariance. These assumptions seem reasonably well met by this data set. We do not feel the covariances of the dependent variables included are significant enough to produce model instability and the data seem linear within the range of speeds observed in this study.

Table 4 – Landing Variable Descriptive Data

Variable	4:00–4:10	4:10–4:20	4:20–4:30	4:30–4:40	4:40–4:50	4:50–5:00
Velocity (m/s)	6.53 ± 0.09	6.28 ± 0.07	6.03 ± 0.08	5.82 ± 0.06	5.60 ± 0.05	5.41 ± 0.06
PVF (BW)	4.5 ± 0.9	4.1 ± 0.6	4.1 ± 0.7	4.2 ± 0.6	4.3 ± 0.9	4.3 ± 0.6
GT** (s)	0.135 ± 0.011	0.141 ± 0.017	0.147 ± 0.019	0.149 ± 0.015	0.156 ± 0.015	0.164 ± 0.018
VIM** (BWs)	0.290 ± 0.035	0.292 ± 0.053	0.302 ± 0.056	0.309 ± 0.039	0.331 ± 0.037	0.345 ± 0.044
HBI** (BWs)	-0.009 ± 0.002	-0.010 ± 0.003	-0.009 ± 0.003	-0.009 ± 0.002	-0.010 ± 0.002	-0.009 ± 0.002
HPI (BWs)	0.046 ± 0.007	0.047 ± 0.007	0.047 ± 0.010	0.051 ± 0.008	0.050 ± 0.008	0.052 ± 0.008
CIV (m/s)	0.36 ± 0.09	0.36 ± 0.07	0.37 ± 0.10	0.41 ± 0.08	0.40 ± 0.08	0.42 ± 0.07
VLR** BW/s)	423.1 ± 108.8	375.3 ± 98.1	378.3 ± 95.9	371.7 ± 78.3	393.4 ± 103.2	389.1 ± 98.2

Mean ± standard deviation. **Indicates statistically significant variables with increasing velocity. VLR ($r^2 = 0.0099$, $p < 0.01$) was positively correlated with increasing velocity and GT ($r^2 = 0.2889$, $p < 0.01$), VIM ($r^2 = 0.1704$, $p = 0.02$), and HBI ($r^2 = 0.0004$, $p = 0.05$) were negatively correlated with increasing velocity.

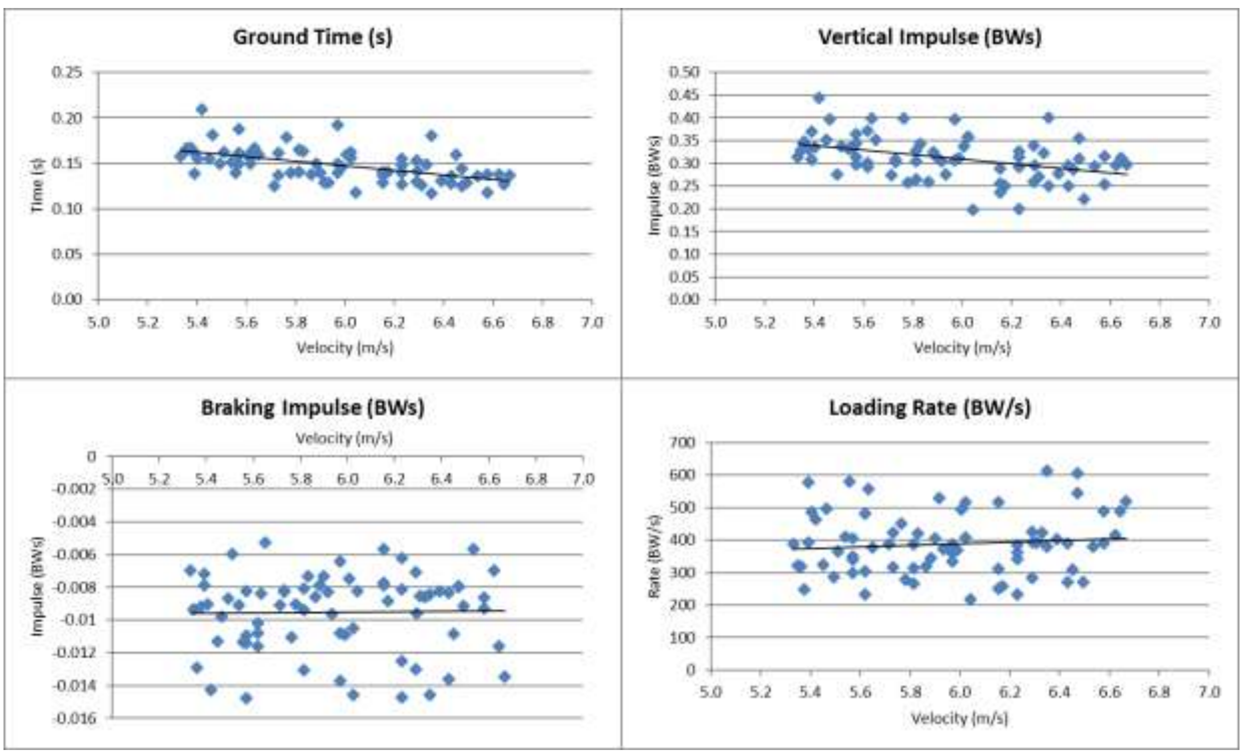

Figure 5-Landing Variable Scatterplots. Individual scatterplots for statistically significant variables correlated with increasing velocity. VLR ($r^2 = 0.0099$, p-value < 0.01) was positively correlated with increasing velocity and GT ($r^2 = 0.2889$, $p < 0.01$), VIM ($r^2 = 0.1704$, $p = 0.02$), and HBI ($r^2 = 0.0004$, $p = 0.05$) were negatively correlated with increasing velocity.

4. Discussion

The purpose of this study was to investigate the effect of increasing pace on the ground reaction forces during steeplechase hurdling takeoff and landing. We observed a positive relationship between increasing velocity and takeoff PVF, takeoff HPI, and landing VLR and a negative relationship between increasing velocity and takeoff GT, landing GT, landing VIM, and landing HBI. These results confirm some of our hypothesized relationships and show that the relationship between increasing velocity and the takeoff and the landing measurements are different. Average takeoff and landing variable values from this study are comparable to the values measured by Kipp et al. after considering the faster average speed of this study.[14]

4.1 Takeoff Ground Reaction Forces

As expected, during hurdling takeoff the PVF increased and the GT decreased as the trial velocity increased which is consistent with other running related studies.[25,26,27] Two of these studies also found that the HPI of running increased with increased velocity as did the HPI of these hurdling trials.[26,27] In addition to the increase in HPI in running, Munro et al. noted an increase in HBI as the running speed increased while our study did not see a statistically significant change in takeoff HBI as the hurdling trial speed increased. This suggested that initiating the hurdling movement alters the step from the normal running pattern and tempers the change in HBI. With the increase in HPI and lack of HBI change, steeplechasers should be able to take off farther back, jump a little lower, and lose less horizontal velocity overall as their hurdle velocity increases.

This analysis suggested that the athlete should prepare through a combined running and strength training program for greater PVF, to generate forces over less time, and to generate greater horizontal push off forces during the takeoff phase of hurdling when increasing velocity.

The majority of the variance explained by our model was by takeoff PVF and takeoff GT with takeoff HPI having a small R^2 value. Despite being statistically significant, it is possible that takeoff HPI may have less practical significance. These preparations will allow athletes to increase their training and racing velocities for the best performance during this phase of hurdling.

4.2 Landing Ground Reaction Forces

The landing ground reaction force variable trends also followed the expected trends with decreased GT and increased VLR as velocity increased similar to overground running.[27] However, it was surprising to see that the hurdling VIM decreased as the trial velocity increased. The decreased VIM is highly related to the decreased ground time. It may also be related to the center of mass continuing to lower until the second support step, the step with the trail leg following the initial landing of the lead leg, as seen in sprint hurdling.[17] One possibility for the decreased VIM on landing as velocity increased is that the athlete may not be in a position advantageous for generating the vertical forces to propel himself upward similar to running. Due to the need to safely navigate the rigid barrier, the subject may be landing with their body in a position that does not allow for efficient or effective production of vertical impulse similar to running. Also, as a runner increases their velocity, their PVF increases, but their GT decreases[25,26]; therefore, the VIM would decrease if the GT decreased more relative to the PVF increase. Another possibility is that in hurdling performance it is not necessary to generate a larger VIM as velocity increases as previously hypothesized. This could be related to the smaller impulse requiring a smaller energy cost; however, there could be an increase in energy cost occurring somewhere else upon landing due to the unusual landing position compared with running. This cost might come during the flight to get the body into a better landing position or it's also possible that the decreased VIM is the best way to land from hurdling at higher velocities. The net energy cost would have to be investigated to know which movements are ideal for overall movement economy.

It was also surprising that HBI increased. Although Munro et al. did note a small increase in magnitude of HBI as speed increased in running, it was hypothesized that the HBI would be reduced on hurdling landing from the different body positioning of landing (the foot typically being farther under the hip in hurdling landing[19]) from a hurdle rather than from running.[27] The foot landing more underneath the body during hurdling, sometimes directly under the center of mass, should result in less braking force. It is possible that the increased velocity made it more difficult to move the landing leg into a position underneath the body prior to landing from hurdling to reduce the HBI, although no kinematic measures were included in this study.

During hurdling landing, this analysis suggested that the athlete should prepare to generate forces over less time, to generate smaller VIM likely through the smaller stance time, to overcome greater amounts of HBI, and to generate the PVF more quickly as the velocity increases. Similar to the takeoff variables, the majority of the variance was explained by the landing GT and landing VIM with landing VLR and landing HBI having small R^2 values. More investigating is needed to determine the practical significance of these variables beyond the statistical significance. Preparing athletes to produce these changes as their training and racing velocities increase will allow them to produce their best performance through the landing phase of hurdling.

This study investigated the kinetics of steeplechase hurdling, but does not address the kinematics related to these forces. Investigations into the kinematics may also reveal the effect of increasing speed on body positioning, in particular the center of mass trajectory.

4.3 Limitations

Data were not taken from within a steeplechase competition; rather, collected in a simulated hurdle setting. It is likely that technique would vary a little in a race due to fatigue, excitement of the race situation, or having other competitors around. For safety, data were collected using a hurdle rather than a traditional steeplechase barrier. While the heights are the same between the hurdles and the barriers, athletes may have modified their technique slightly since the hurdles are less of a risk for injury. Data could not be collected for takeoff and landing for a single jump which required 2 separate statistical analyses. However, we were still able to find sufficient statistical power to answer the questions of interest due to having multiple trials of each condition.

4.4 Training Program and Injuries

Previous research already showed greater forces in steeplechase hurdling compared with treadmill running.[14] We now also know how these forces change as hurdling speeds increase. In preparation for a steeplechase season, and while increasing speed as fitness improves, steeplechasers should be careful to follow principles of adaptation to stress allowing the body to recover from stress and build strength. Training plans included in the buildup to a season of steeplechasing and throughout the competitive season, including drills and exercises that strengthen the muscles, the tendons, and the bones expected to be affected by hurdling, should help minimize injury risk while building strength and power.

Plyometric training has been shown to increase lower leg power and knee extensor strength in male soccer players,[29] decrease ground contact time during an agility test,[30,31] and improve measures of neuromuscular power and control.[32] Lateral hopping plyometrics produced benefits for leg power through higher peak force, peak rate of force development, and impulse compared to lateral speed plyometrics which produced benefits for foot strike frequency through shorter ground contact times.[33] Many runners incorporate plyometrics into their training programs and these data suggest the plyometrics are of greater importance in steeplechase training. Resistance and plyometric training will also prepare the body to withstand the forces that occur above normal running.[34,35,36,37]

As velocity increased, many of the changes in ground reaction force variables of hurdling were similar to the changes noted in running as velocity increased. As a result, training focused on better performance at higher running velocities will benefit the athlete in steeplechase hurdling performance as well. However, because some differences were noted, the steeplechase athlete will still benefit from steeplechase hurdling-specific workouts and exercises to prepare specifically for the steeplechase event.

4.5 Further Study

Our statistical analysis showed significant correlations between many variables. The best-fitting models for takeoff and landing were used in this discussion. Some excluded variables appeared to be related to changes in velocity, but were determined to be nonsignificant when the more significant variables were included in the model first. Therefore, although the excluded variables in each analysis are not as strongly connected with changes in velocity as the ones reported, they still warrant further investigation and should be considered as meaningful variables to steeplechase hurdling performance.

This study adds to the knowledge of the steeplechase event through the effect of increasing velocity on ground reaction force variables; however, there is much left to learn about steeplechase performance. Other areas of study that would also contribute to the understanding of the steeplechase event would be how changes in velocity influences the kinematics of steeplechase hurdling, the ground reaction forces during water jump obstacle navigation, the variability of the ground reaction forces during hurdling and water jump clearance, how the approach steps and second support landing steps interact with the obstacle navigation, and how different training protocols may affect the ground reaction forces and event performance.

5. Conclusion

This study was the first to examine how ground reaction force variables change in steeplechase hurdling as velocity increases. As male steeplechasers prepare to hurdle at increasing speeds, they produce a greater PVF on the takeoff step while decreasing the GT during takeoff, and increasing the HPI to carry themselves beyond the hurdle. While landing from the hurdle at increasing speeds, the athlete decreased the amount of time spent on the landing stance, decreased the VIM, and the magnitude of HBI and VLR increased. The greater forces resulting from increased velocity requires runners to carefully adapt to the faster race paces towards which they are training in order to protect themselves from injury. Since the forces are changing, different body positions are likely occurring as well. Thus, steeplechasers may need training time focused on technique in addition to physiological conditioning as they progress to greater velocities.

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