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Variations in Running Form Among Female Sprinters, Middle, and Distance Runners

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VARIATIONS IN RUNNING FORM AMONG FEMALE SPRINTERS,

MIDDLE, AND DISTANCE RUNNERS

by

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GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

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This thesis has been read by each member of the following graduate committee and by a majority vote has been found satisfactory.

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BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the thesis of Ruthann Cunningham in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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ABSTRACT

VARIATIONS IN RUNNING FORM AMONG FEMALE SPRINTERS, MIDDLE, AND DISTANCE RUNNERS

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Master of Science

In the sport of track and field, runners excel at their events due not only to physiological characteristics but aspects in their form. Characteristics in form help runners achieve the goal in completing their event in the least amount of time possible. For sprinters, this is done by having a shorter swing phase and ground time along with greater power and a longer stride length. Distance runners accomplish the goal of quicker speeds by balancing it with running economy by spending greater time on the ground with shorter stride lengths compared to those in shorter distance running events. Middle distance runners must find a balance between power and running economy for greater success in the 800 meter and 1600 meter runs. If these characteristics are true for runners while competing in their event, would they also be seen at speeds slower and faster than what they compete at? **Purpose:** This study was conducted to determine if sprinters, middle distance runners, and distance runners running at the same speeds would exhibit different characteristics in their form which aid them in their events. **Methods:** Thirty female Division I collegiate runners participated in this study. Runners were separated into categories based on the events they were currently training in: 10 sprinters, 10 middle distance runners, and 10 distance runners. All participants were asked to run for twenty two steps at 3.17 m/s (8:27 min/mile), 3.58 m/s (7:30 min/mile), 4.11 m/s (6.31 min/mile), 4.87 m/s (5:30 min/mile), and 5.95 m/s (4:30 min/mile) pace. Motion analysis was captured at each speed recording knee angles, ground time, center of mass separation, and stride length at 240 Hz. Data was then processed using ANOVA and a Tukey post hoc analysis. **Results:** Significant differences ($p < .05$) occurred between distance runners and the groups of middle distance runners and sprinters in knee range, ground time, center of mass separation, and stride length while running at the same speed for all of the five speeds. All groups displayed similar liner slopes as speeds increased with no interactions occurring between groups. As the speed increased, all three groups decreased in knee range measurements and ground time measurements. Increases in speed displayed and increase in center of mass separation and stride length among all three groups. **Conclusion:** While running at the same speeds, runners exhibit specific characteristics in their form that benefit them in their event. These are even seen in speeds that are faster or slower that what the athletes are used to training at or competing at. In addition, middle distance runners display aspects of form that are between distance

runners and sprinters in all variables. By understanding these differences, coaches and athletes can analyze current performance and make needed adjustments.

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Variations in Running Form Among Female Sprinters, Middle, and Distance Runners.

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Abstract

In the sport of track and field, runners excel at their events due not only to physiological characteristics but aspects in their form. Characteristics in form help runners achieve the goal in completing their event in the least amount of time possible. For sprinters, this is done by having a shorter swing phase and ground time along with greater power and a longer stride length. Distance runners accomplish the goal of quicker speeds in combination with consideration of running economy compared to those in shorter distance running events. Middle distance runners must find a balance between power and running economy for greater success between 800 and 3000 m runs. This difference in style of race may lead to differences in movement patterns between different events. **Purpose:** This study was conducted to determine if sprinters, middle distance runners, and distance runners running at the same speeds would exhibit different characteristics in their form. **Methods:** Thirty female Division I collegiate runners participated in this study. Runners were separated into categories based on the events they were currently training in: 10 sprinters, 10 middle distance runners, and 10 distance runners. All participants were asked to run for twenty two steps at 3.17 m/s (8:27 min/mile), 3.58 m/s (7:30 min/mile), 4.11 m/s (6.31 min/mile), 4.87 m/s (5:30 min/mile), and 5.95 m/s (4:30 min/mile) pace. Motion analysis was captured at each speed to obtain knee angles, ground time, center of mass separation, and stride length at 240 Hz. Data was then processed using ANOVA and a Tukey post hoc analysis. **Results:** Significant differences ($p < .05$) occurred between distance runners and the groups of middle distance runners and sprinters in knee range, ground time, center of mass separation, and stride length while running at the same speed for all of the five speeds. As the speed increased, all three groups decreased in knee range measurements and ground time measurements. Higher speeds increased center of mass separation and stride length among all three groups. All groups displayed linear slopes as speeds increased with no interactions occurring between groups. **Conclusion:** While running at the same speeds, runners exhibit specific characteristics in their form that benefit them in their event. These are even seen in speeds that are faster or slower than what the athletes are used to training or competing at. In addition, middle distance runners display aspects of form that are between distance runners and sprinters in all variables. By understanding these differences, coaches and athletes can analyze current performance and make needed adjustments.

Introduction

Discovering what contributes to running success helps coaches and athletes improve and changes competition. One area of running research is the differences in form between sprinters, middle, and distance runners at various speeds. Research has found running forms and body positions that aid in runners' top speed in several different running events (Williams, Cavanagh, & Ziff, 1987; Kyrolainen, Belli, & Komi, 2001; Nummela, Keranen, & Mikkelsson, 2007; Williams & Cavanagh, 1987). However, little research exists to show if differences in form exist among sprinters, middle, and distance runners while running at the same speed. Discovery of differences in can aid athletes in improving performance by identifying aspects of their form that if slightly improved will decrease overall running time and increase velocity.

One area that benefits runners in performance is knee flexion during the stance phase of running. During this time a runner can influence the power of toe off by the amount of knee flexion. Sprinters display this smaller knee range due to the emphasis on power while distance runners benefit in a slightly larger knee range during their events in order aid in running economy (Novacheck, 1998). When comparing sprinters and distance runners at maximal speed, sprinters display less knee flexion than distance runners during ground contact (Bushnell & Hunter, 2007). With known changes that occur in knee angles, research can be furthered to determine if changes occur at the same speeds between sprinters, middle, and distance runners with increases in speed and if modifications in knee range would benefit a category of runners.

Stride length also contributes to the success of a runner (Cavanagh, 1987; Nummela et al., 2007). When a runner increases speed, stride length increases even with a self-selected optimal stride lengths displayed by each runner (Nummela et al., 2007). Despite natural differences in stride length, similarities exist within groups. Sprinters have a longer stride length compared to distance runners (Armstrong et al., 1984; Bushnell & Hunter, 2007). Further research can identify characteristics in stride length displayed by each group at various speeds. Findings my improve performance at maximal speeds.

Variations between sprinters and distance runners have also been noted with the horizontal displacement between the landing toe and center of mass (center of mass separation) at ground time. Bushnell and Hunter (2007) studied these ideas, comparing male distance runners and sprinters running at the same pace. The center of mass separation was smaller with sprinters compared to distance runners at submaximal and maximal speeds. This may be due to the need for sprinters to produce more power for take off. The closer the landing toe is to the center of mass the greater the power that may be produced. Results also indicated sprinters spent less time on the ground at submaximal and maximal speeds which may aid in a quicker velocity. Studying a wider range of speeds would provide greater insight into variations between the three groups of runners.

Researchers have found what causes individual variations in running as well as similarities that occur in running groups such as sprinting, middle distance, and distance. However, little research exists comparing these groups of female runners to each other while running at the same pace.

The purpose of this study is to investigate potential variations in form among intercollegiate female sprinters, middle distance, and distance runners while running at the same speeds. We hypothesized that 1) greater knee flexion would be seen with distance runners at each speed, 2) greater ground time would occur with distance runners, 3) greater center of mass separation would be seen with distance runners, 4) greater stride length would be seen with sprinters at each speed, and 5) each group would display an increasing in stride length and ground time and a decrease in knee range and ground time with increases in speed. Middle distance runners would display measurements between sprinters and distance runners.

Methods

Participants

Thirty female runners from a Division I collegiate track and field team were recruited for this study. These participants were grouped into one of three running categories based on the distances they compete at: sprinters (400 meters and less), middle distance (800 meters to 1600 meters), and distance runners (3000 meters and greater). Ten participants were selected for each category (Table 1).

Procedures

While in training season, each participant completed one session of running. Measurements for each participant were taken to determine joint centers and form marker placements according to the Vicon Plugin Gait Model (Vicon Motion Systems Ltd., Oxford, UK). Runners performed all trials on the same treadmill in a biomechanics lab using Vicon Nexus 1.3 (Vicon Motion Systems Ltd, Lake Forest, CA) with six MX 13+

cameras running at 240 Hz. All data and measurements were collected and processed with Vicon Nexus software.

All runners performed the trial wearing racing flats (Nike® Zoom Waffle Racer™). A five-minute warm up was given to allow each runner to adjust to treadmill running. After the warm up, runners ran 22 steps at each speed followed by an immediate increase to the next higher speed ((3.17 m/s (8:27 min/mile), 3.58 m/s (7:30 min/mile), 4.11 m/s (6.31 min/mile), 4.87 m/s (5:30 min/mile), and 5.95 m/s (4:30 min/mile)). The total time for data collection after the warm up was three minutes.

Knee range (KR) (range of motion of the knee from ground contact to maximum flexion during stance), ground time (GT) (amount of time on the ground during stance phase), center of mass separation (CMS) (horizontal distance from the center of mass to the front of the toe at touchdown), and stride length (SL) (the vertical distance divided by time in the air) for each speed calculated using a customized program (Microsoft Visual Basic.NET). A customized Excel spreadsheet (Microsoft, Redmond, Washington) then calculated averages for eight strides. Due to a lack of significant difference between left and right legs, the two variables were combined to calculate the average of each stride for KR, GT, and CMS.

Statistical Analysis

Difference between groups at each speed were tested using ANOVA with a Tukey post hoc test for each of the four variables; KR, GT, CMS, and SL. CMS and SL were normalized for height. The alpha was set at 0.05.

Results

Knee Range

KR results showed significant differences in KR between distance runners compared to middle distance and sprinters (Table 2). Across all speeds, sprinters displayed a smaller KR compared to distance runners and middle distance runners displayed smaller KR compared to distance runners.

Changes in KR due to speed was also determined for each group of runners. It was found that as the speed increased, each group's KR in degrees became smaller (Table 2). Runners who compete at higher speeds and higher overall speeds show a smaller KR at touchdown.

Ground time

Results showed significant differences in GT between distance runners and middle distance and sprinters at each speed (Table 3). Sprinters spent the least amount of GT followed by middle distance runners then distance runners.

When comparing differences within each group it was found that as speed increased, all three groups of runners spend less time on the ground (Table 3).

Center of Mass Separation

Results indicated CMS was significantly different between distance runners to that of middle distance runners and sprinters at all speeds (Table 4).

Increases in speed caused the CMS increased in all groups (Table 4).

Stride Length

Sprinters had the greatest SL and distance runners displayed the shortest SL at each speed (Table 5). Within group changes due to speed also displayed changes in SL. As speed increased each group displayed an increase in SL (Table 5).

Discussion

Our study and results found these primary things: 1) at all five speeds, distance runners had the greatest knee range, 2) at all speeds, distance runners had the longest ground time, 3) at all speeds, distance runners had the greatest center of mass separation, 4) at all speeds, distance runners had the shortest stride length, and 5) with speed increases, each group displayed a descending slope in knee range and ground time and an ascending slope in center of mass separation and stride length.

Knee Range

Prior research has supported the finding in differences in KR occurring between sprinters and distance runners at various speeds (Bushnell & Hunter, 2007; Mann, Moran, & Dougherty, 1986; Novacheck, 1998). Smaller knee angles displayed by sprinters are due to greater leg stiffness during the stance phase. This greater leg stiffness allows sprinters to spend less time on the ground along with generating greater power during toe off (Bushnell & Hunter, 2007). During the last lap of a middle distance and distance race when the emphasis shifts from economy to velocity, a smaller knee range can aid in producing greater power.

As the speed increased, all three groups of runners displayed a smaller KR. Smaller KR have been seen in previous research when jogging and running speeds were compared to sprinting speeds (Mann et al., 1986; Novacheck, 1998). A smaller KR at maximal speeds can benefit all groups by spending less time on the ground while generating more power for toe off.

Ground Time

GT is the second variable we chose to observe. Bushnell & Hunter (2007) found that at maximal speeds, sprinters have a shorter GT than distance runners which help them obtain a higher velocity and reduces breaking impulses. When comparing stance time at various percentages of maximum velocity, the mean stance time was longer at lower percentages compared to the higher percentages (Kivi et al., 2002). The decrease in GT with increasing speed allows the runner to achieve a higher velocity by spending less time on the ground. As the velocity increases, runners need to know the most effective way to reduce GT for their event for performance.

As speed increased, the GT for each group decreased. Decreases in GT due to increasing speed aids runners in obtaining maximal speeds (Kivi, Maraj, & Gervias 2002; Mann, 1985). This is beneficial not only to sprinters but also middle distance and distance runners at top speeds.

Middle distance and distance runners benefit by implementing the sprint like technique to reduce GT at top speeds (Paavolainen, Häkkinen, Hämäläinen, Nummela, & Rusko, 1999; Saunders, Telford, Pyne, Peltola, & Cunningham, 2006). When a middle distance or distance runner is on the last lap the focus shifts to increasing velocity instead of economy. In this case, training that allows runners to decrease GT may benefit these two groups of runners.

When statistically looking at the differences in GT between the three groups, results show minimal differences to the 100^{th} of a second (Table 3). With little variation, the question poised is if statistically significant differences are practical in the event itself. In high velocity running events these slight differences in GT are important. Often at the end of a race the finish between athletes comes down to the 100^{th} of a second. Finding ways to decrease even a 100^{th} of a second from the overall time can make the difference between second palace and first place in a high velocity finish.

Center of Mass Separation

Differences in center of mass separation are due to the different groups focus on power and economy. Previous studies have also seen differences occurring between sprinters and distance runners when measuring CMS (Bushnell & Hunter, 2007). Sprinters bring their legs though the swing phase as quickly as possible, placing the landing leg as close to their center of mass. This allows them to produce more power and decrease GT. Distance runners are more concerned with running economy, displaying a longer CMS and GT. At maximal speeds, middle distance and distance runners may benefit by decreasing CMS. This would allow them to produce greater power during maximal speeds.

An increase in the center of mass separation with increasing speed may be due to increasing stride length. The calculations for SL and CMS are different but interactions between the two variables may occur. SL is the distance the center of mass travels during two steps. CMS is the horizontal distance from the center of mass to the front toe at touchdown. There may be a connection between these two measurements, but this study did not make that connection. Future research may look into exactly what determines stride length differences.

Stride Length

Sprinters display a greater SL then distance runners when competing at their race speeds (Armstrong, Costill, & Gehlsen, 1984; Bushnell & Hunter, 2007). Longer SL displayed by sprinters at higher speeds allows them to maximize velocity with power. Again, middle distance and distance runners may benefit from training that focuses on reducing ground time which would lead to a greater stride length. This specific training is beneficial when the focus shifts from economy to velocity. This could aid in decreasing final lap time and increasing velocity.

Additionally, previous research states that as speed increases, SL increases to benefit sprinters and distance runners (Cavanagh & Kram, 1989; Mann, 1985). This increase in SL at increasing speeds is a result of a decrease in GT time and flight time (Cavanagh & Kram, 1989; Kivi et al. 2002; Kyrolainen et al., 2001; Nummela et al., 2007; Weyand, Sternlight, Bellizzi, & Wright, 2000; Williams & Cavanagh, 1987). In order to improve performance at higher speeds, sprinters, middle distance, and distance runners can decrease GT and increase SL to achieve a higher velocity.

With an increase in SL at higher velocities the question is how much of an increase will actually benefit the runner. Statistically significant differences between distance runners and middle distance and sprinters were less than a 10^{th} of a meter (Table 5). Over the course of a race this small difference in one SL becomes significant to overall race velocity. Slight variations in SL can have a large impact on overall performance.

Limitations

Findings in this study show that at the same speed sprinters, middle distance, and distance runners all display differences in KR, GT, CMS, and SL. After following validated procedures from previous studies, some error may have occurred due to various factors. KR data was determined from marker placement on the knee joint center by the Vicon Nexus system. While care was taken to place markers over the knee joint, error may have occurred due to skin movement and differences in body types. This error is minimal due to results which show differences between the groups and the similarities with previous findings (Mann et al., 1986; Novacheck, 1998).

Considerations in error are also in SL and KR results due to the running surface. Runners completed all trials on a treadmill instead of an overground surface. Differences in running surface may have affected the SL and KR at touchdown due to different ground reaction forces. Again, error between individuals is minimal due to the fact that all runners ran on the same surface, minimizing the differences between groups.

Lastly, this study is limited due to the participants. Only runners competing at a Division I collegiate level participated in this study. With a narrow population, findings may be seen in other populations but further research is needed.

Conclusion

Coaches and athletes make needed adjustments to improve performance. Significant differences in knee range (KR), ground time (GT), center of mass separation (CMS), and stride length (SL) are seen between distance runners and the groups of middle distance runners and sprinters. With these differences, the variables either increase or decrease with the distance the group competes at.

These findings can aid collegiate coaches and athletes in improving running performance in their specified events. Sprinters can identify areas of training that will increase velocity by further reducing knee range, decreasing ground time and center of mass separation, and increasing stride length. Middle and distance runners may include more sprint like training in these four variables to aid in the last lap of events that are performed at higher velocities. In addition, with further research coaches of novice runners may take these findings and use them to identify characteristics of a runner. These characteristics may aid the coach in suggesting and training the athlete for events that may best fit characteristics displayed in their running form.

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Table 1: Subject Characteristics

Characteristics	Sprinter	Middle Distance	Distance
Mean height (m)	1.695	1.712	1.693
SD height (m)	.047	.044	.062
Mean mass (kg)	60.40	58.31	55.44
SD mass (kg)	5.40	3.64	4.33
Mean age	19.80	18.80	19.30
SD age	2.49	.92	1.16

Table 2: Knee Range

Speed (m/s)	Sprinter (A) Knee Range (deg)		Middle Distance (B) Knee Range (deg)		Distance (C) Knee Range (deg)	
	M	*SD*	*M*	*SD*	*M*	*SD*
3.17	25.8 ^{C}	4.521	26.8 ^{C}	2.175	32.5 ^{AB}	8.637
3.58	26.2 ^{C}	4.616	25.5 ^{C}	4.019	30.8 ^{AB}	5.896
4.11	26.0 ^{C}	4.797	25.9 ^{C}	3.392	32.3 ^{AB}	4.672
4.87	23.9 ^{C}	3.523	26.2 ^{C}	2.845	32.8 ^{AB}	5.094
5.95	22.8 ^{C}	3.866	24.7 ^{C}	3.565	30.9 ^{AB}	4.485

Note. Superscripts (A,B,C) indicate differences between groups at $p < .05$ in the Tukey post hoc analysis (i.e. a variable with a superscript denotes the variable is significantly different from the other superscripted variables).

Table 3: Ground Time

Speed (m/s)	Sprinter (A) Ground Time (s)		Middle Distance (B) Ground Time (s)		Distance (C) Ground Time (s)	
	M	*SD*	*M*	*SD*	*M*	*SD*
3.17	.22 ^{C}	.018	.23 ^{C}	.028	.25 ^{AB}	.020
3.58	.21 ^{C}	.015	.21 ^{C}	.026	.23 ^{AB}	.017
4.11	.18 ^{C}	.016	.19 ^{C}	.020	.21 ^{AB}	.014
4.87	.16 ^{C}	.016	.17 ^{C}	.020	.19 ^{AB}	.016
5.95	.14 ^{C}	.011	.14 ^{C}	.017	.16 ^{AB}	.013

Note. Superscripts (A,B,C) indicate differences between groups at $p < .05$ in the Tukey post hoc analysis (i.e. a variable with a superscript denotes the variable is significantly different from the other superscripted variables).

Table 4: Center of mass separation

Speed (m/s)	Sprinter (A) Center of Mass Separation (m)		Middle Distance (B) Center of Mass Separation (m)		Distance (C) Center of Mass Separation (m)	
	M	*SD*	*M*	*SD*	*M*	*SD*
3.17	.179 [C]	.013	.189 [C]	.020	.207 [AB]	.033
3.58	.184 [C]	.015	.188 [C]	.028	.211 [AB]	.023
4.11	.189 [C]	.014	.196 [C]	.024	.219 [AB]	.015
4.87	.191 [C]	.022	.207 [C]	.020	.230 [AB]	.020
5.95	.200 [C]	.015	.214 [C]	.028	.243 [AB]	.018

Note. Superscripts (A,B,C) indicate differences between groups at $p < .05$ in the Tukey post hoc analysis (i.e. a variable with a superscript denotes the variable is significantly different from the other superscripted variables).

Table 5: Stride Length

Speed (m/s)	Sprinter (A) Stride Length (m)		Middle Distance (B) Stride Length (m)		Distance (C) Stride Length (m)	
	M	*SD*	*M*	*SD*	*M*	*SD*
3.17	1.305 [C]	.053	1.305 [C]	.041	1.294 [AB]	.074
3.58	1.461 [C]	.063	1.439 [C]	.047	1.430 [AB]	.083
4.11	1.627 [C]	.072	1.605 [C]	.067	1.589 [AB]	.098
4.87	1.819 [C]	.081	1.787 [C]	.084	1.763 [AB]	.113
5.95	2.043 [C]	.092	2.004 [C]	.079	1.953 [AB]	.126

Note. Superscripts (A,B,C) indicate differences between groups at $p < .05$ in the Tukey post hoc analysis (i.e. a variable with a superscript denotes the variable is significantly different from the other superscripted variables).

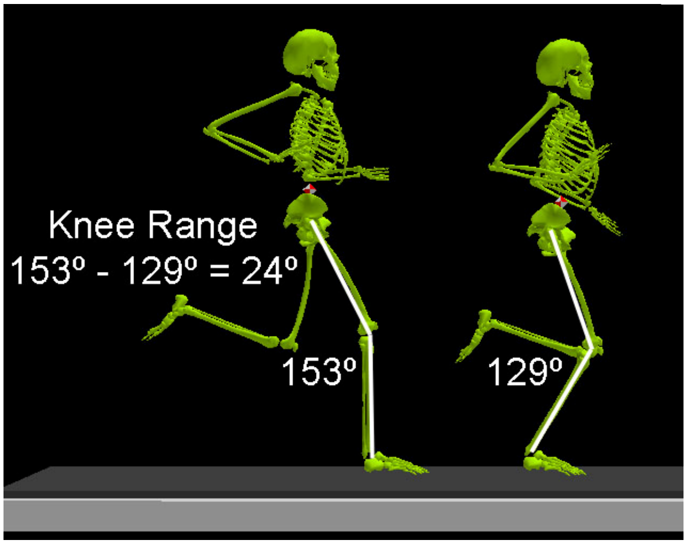

Figure 1: Knee range at touchdown

Note. Knee range is calculated from the point of ground contact to the maximal flexion of the knee during ground time.

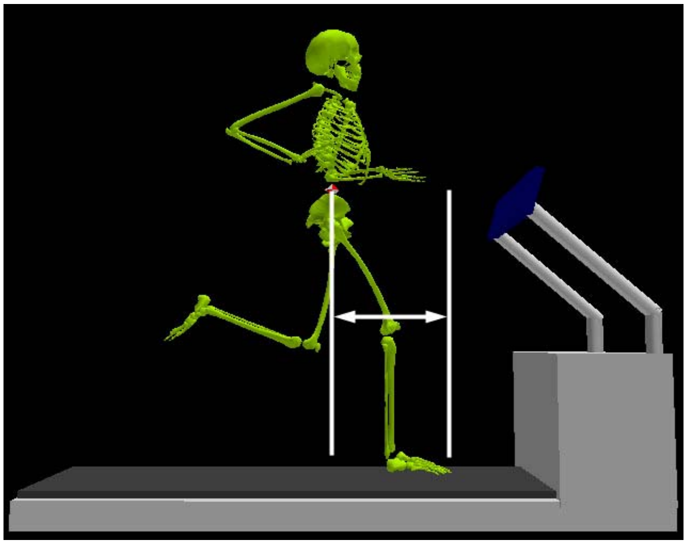

Figure 2: Center of Mass Separation

Note. Center of mass separation is calculated from the initial ground contact phase of the lead foot. Measurement is based on the distance from the toe to the center of mass.

Appendix A

Prospectus

Chapter 1

Introduction

Discovering what contributes to running success helps coaches and athletes improve and change competition. One area of running research is the biomechanical differences in form between sprinters, middle, and distance runners at various speeds. Research has found running forms and body positions that aid in runners' top speed in several different running events (Kyrolainen, Belli, & Komi, 2001; Nummela, Keranen, & Mikkelsson, 2007; Williams & Cavanagh, 1987; Williams, Cavanagh, & Ziff, 1987). However, little research exists to show if differences in form exist among female sprinters, middle, and distance runners while running at the same speed. Discovery of possible differences can aid athletes in greater running performance.

Researchers have focused on finding what contributes to top running form of elite sprinters, middle, and distance runners. They have studied if differences in stride length and stride frequency contribute to the success of a runner (Cavanagh, 1987; Nummela et al., 2007). When a runner increases speed, stride length and stride frequency increase but each runner has a self-selected optimal stride length and no set standard can be applied to all runners (Nummela et al., 2007). This self-selected stride causes natural variations in form to occur between runners. Despite natural differences in form due to stride length, similarities exist with the changing of runners' form when running at lower speeds compared to higher speeds.

An increase in speed also changes knee movements and ground contact time (Nummela et al., 2007; Vaughan, 1984; Williams & Cavanagh, 1987). In the knee, changes in the angle of flexion and extension occur. The maximum knee flexion increases from running to sprinting in the swing phase of the gait cycle and the absorption period of the knee decreases from running to sprinting (Novacheck, 1998). With known changes that occur in knee angles, research can be furthered to determine if changes occur at the same rates between sprinters, middle, and distance runners with increases in speed.

Bushnell and Hunter (2007) studied this idea, comparing male distance runners and sprinters running at the same pace. Significant differences were found between the two groups at the position of the recovery knee at touchdown compared with the center of mass. These specific results indicate that there are differences between the two groups at maximal and submaximal speeds.

In addition to runners having difference in stride length, stride frequency, and body segment angles, Kyrolainen et al. (2001) stated that variations between runners occur due to age, sex, body temperature, body weight, and muscle fiber distribution. These variations may also contribute to variations in form among sprinters, middle distance, and distance runners.

Researchers have found what causes individual variations in running as well as similarities that occur in running groups such as sprinting, middle distance, and distance. However, little research exists comparing these groups to each other while running at the same pace with a focus on female runners.

The purpose of this study is to find if there are natural variations in form among intercollegiate female sprinters, middle distance, and distance runners while running at the same speeds. This study will analyze the knee ranges, ground contact time, center of mass separation, and stride length between these three groups of female runners. Results will determine if natural variations among runners occur. If each group exhibits a natural pattern in their form, coaches and athletes can use this information for the selection and training of athletes in specific events based not only on physiological factors but also the natural characteristics the runner exhibits in form that may predispose them to excel in specific running distances.

Purpose Statement

The purpose of this study is to compare sprinters, middle distance, and distance runners form while running at the same speeds.

Hypothesis

There are variations in form between female collegiate distance, middle distance, and sprinters running at the same five selected speeds. We formulated four hypotheses to test this expectation:

1. Center of mass separation will be significantly greater for middle distance runners, relative to long distance runners, and for sprinters relative to middle distance runners.
2. Knee ranges will be significantly smaller for middle distance runners, relative to long distance runners, and for sprinters relative to middle distance runners.
3. An increase in stride length will be seen from middle distance runners to sprinters and from distance runners to middle distance runners.
4. Sprinters will have a shorter ground contact time compared to middle distance runners and middle distance runners will have a shorter ground contact time compared to sprinters.

Null Hypothesis

There is no variation in form between distance, middle distance, and sprinters running at the same speed.

Assumptions

Each subject will be free from injury or have fully recovered from injury and illness.

Delimitations

1. Subjects are current NCAA Division I female intercollegiate distance, middle distance, and sprinters between the ages of 18 and 25 years.
2. Participants are injury free and in training season.
3. All of the trials will be done on a treadmill.
4. All of the participants will wear the same type of running shoe.

Limitations

1. Subjects may not correctly report injury and training status.
2. Form may have slight variation on the treadmill compared to overground running.

Definitions

Biomechanics - study of forces and the mechanics of the human body

Center of mass separation - the horizontal distance between the center of mass to the front toe at touchdown

Distance runners - races longer than one mile up to the marathon

Gait - movement of body limbs and changes in ground time

Gait cycle - movement of lower body limbs and the ground contact time

Ground contact time – amount of time the foot is in contact with the ground

Knee range – the amount of flexion in the knee during stance phase

Middle distance runners – 800-meter run through the mile run

Sprinters - distances shorter than the 800-meter run

Stance phase - when the foot is in contact with the ground

Stride frequency - The time touchdown of one foot divided by the subsequent touchdown of the same foot measured in strides/second or Hz.

Stride length - The distance between the touchdown of one foot and the next touchdown of the same foot

Swing phase - when the foot is not in contact with the ground.

Significance of Study

The significance of this study covers two main purposes. The first is to determine if sprinters, middle distance, and distance runners exhibit differences in form while running at the same speed. It is known that variations exist among distance runners and sprinters while they are competing in their specified category. It is also known that sprinters and distance runners exhibit differences in form while running at maximal speeds. It is hoped that by comparing sprinters, and distance runners, along with middle distance runners, it can be determined if differences only occur between sprinters and distance runners or if middle distance runners also exhibit differences from the two aforementioned groups.

The second purpose is to determine at what speeds these differences are exhibited. Distance runners display unique differences from sprinters in knee ranges, ground contact time, center of mass separation, and stride length while running at higher speed. These differences are due to the need for sprinters to have power and speed compared to distance runner who must balance running economy and speed. Do these same differences also exist among the two groups at slower speed where power becomes less of an emphasis and running economy has a greater influence then higher speed? If differences do exist at slower speeds, is it due to a constant aspect in form each group displays at any speed or do significant differences only occur at higher speeds?

This study will determine of sprinters, middle distance, and distance runners all display significant differences from each other in form. If differences do occur, it will also provide an understanding as to which speeds these differences in knee angles, ground time, center of mass separation, and stride length are seen.

Chapter 2

Review of Literature

Researchers have analyzed various biomechanics during the running cycle. Hip angles, knee angles, ground time, stride length, stride frequency, and center of mass oscillation are all examples of different aspects that have been studied. A variety of subjects from casual runners to elite athletes, sprinters to long distance runners, and male and female runners have also been studied. This information has furthered running knowledge and improved performance. However, an area of this research that has little information is comparing the running form of elite female runners, who compete in different events, running at the same speeds. Comparing the forms of female sprinters to middle and distance runners at the same speeds can further increase understanding of proper form, body angles, ground time, and stride length. Additionally aspects of form that contribute to female runners' success in specified running distances may be identified.

Lower Extremity Biomechanics

There are many different changes that occur in the legs with increases in running speeds. Leg measurements include areas of stride length, stride frequency, ground time, and knee angles. These measurements vary between individuals and change with increasing speed.

Stride Length and Stride Frequency

Stride length and stride frequency are common measurements conducted in running research. . Both are found to be self-selected for individuals and over time self-selection is usually the optimal or the most comfortable and natural stride length for that person (Cavanagh, Andre, Kram, Rodgers, Sanderson, & Henning, 1985; Cavanagh, 1987; Saunders, Pyne, Telford, & Hawley, 2004; William & Cavanagh, 1987). With variations in stride length and frequency among runners further studies have analyzed modifications made to these areas, how speed affects stride length and frequency, and common forms of stride length and frequency in distance runners and sprinters.

Cavanagh et al. (1985) analyzed the effects of modifications in stride length in individuals. He found chosen optimal stride length may vary in an individual from day to day. Modifications can be made in a runner's stride length, but this may affect other systems in the body. Changes in stride length may change oxygen cost as well as having minor metabolic consequences for the individual. Cavanagh et al. (1985) concluded that stride length is unique to the individual physiology of each runner and a general template cannot be applied to all runners.

Along with individual variations in stride length, changes occur as speed changes. It has been observed that an increase in velocity increases stride length as well as stride frequency due to a decrease in ground contact time and flight time (Cavanagh & Kram, 1989; Kivi, Maraj, & Gervais, 2002; Kyrolainen et al., 2001; Nummela et al., 2007; Weyand, Sternlight, Bellizzi, & Wright, 2000; Williams et al., 1987). At higher speeds, stride frequency plays a greater role than stride length (Nummela et al., 2007; Weyand et al., 2000). At lower speeds, increase in speed is caused by increases in stride length but not stride frequency (Cavanagh & Kram, 1989). To use one template as an optimal stride length for distance running and sprinting is not plausible.

Physiology as well as biomechanics contributes to successful distance runners stride length and stride frequency. Anderson (1996), Cavanagh et al. (1985), Cavanagh (1987), and Saunders et al. (2004) observed a good distance runner will have a freely chosen stride length for optimal running economy. Marathoners on average have a shorter stride length than those competing in shorter running events while stride frequency of a distance runner is the same compared with other runners (Armstrong, Costill, & Gehlsen, 1984). As the velocity of a distance runner increases, the stride length of the runner also increases, but this is not seen in the relationship between velocity and stride frequency of distance runners (Cavanagh & Kram, 1989). Successful distance runners have differences in stride length, but similar stride frequencies.

For a sprinter, success is determined by their stride length (Mann, 1985). Sprinters have a longer stride length compared to distance runners and this provides a greater contribution in top speeds (Armstrong et al., 1984; Bushnell & Hunter, 2007). Adaptations to stride length may be the result of training, muscular adaptations or improved leg strength, which determines sprinters stride length (Mann, 1985). If a sprinter were to improve their leg strength they would see changes in stride length that may benefit their overall performance (Mann, 1985).

Ground Time

Ground time decreases as speed increases. Ground time is defined as the amount of time each foot is on the ground during the stance phase of running. This is the only phase during running where the runner can produce force and influence their stride length and speed (Nummela et al., 2007). As the speed increases, there is generally a decrease in the contact time (Kyrolainen et al., 2001; Mann, Moran, & Dougherty, 1986). Weyand et al. (2000) found that faster runners not only had less ground contact time but were able to apply greater force during this contact time. Force that is applied during ground contact time will linearly increase with the running speed, aiding distance runners in top speeds (Nummela et al., 2007). Ground time is an important aspect in running performance.

Ground time and vertical oscillation for distance runners varies with the speed of the runner. For distance runners with slower running gaits, ground contact times were longer. With a longer ground contact time there was a lower maximum vertical force at peak. The time spent on the ground is critical to produce a horizontal ground reaction force that will help the distance runner gain their top running speed compared to that of the vertical ground force (Nummela et al., 2007). Additionally, many good distance runners have a lower vertical oscillation even though their ground contact time is shorter than untrained distance runners (Anderson, 1996). This lower vertical oscillation causes the runner to have a lower center of mass while running long distances which aids in better running economy (Saunders et al., 2004). Trained distance runners have lower vertical oscillation and shorter ground contact times than untrained.

An ideal sprinter will decrease ground contact time. Bushnell and Hunter (2007) studied differences in ground contact time between male sprinters and distance runners at the same speeds, and found that sprinters have a lower ground contact time. Kivi et al. (2002) compared stance time at 70%, 80%, 90%, and 95% of maximum velocity, and found that mean stance time was longer when running at 70% through 90% of maximum velocity compared to 95%. Better sprinters will focus on decreasing their ground contact time to aid in maximum speeds (Mann, 1985).

With a shorter ground contact time, effective sprinters produce a greater force during the toe-off phase, contributing to increases in overall speed (Weyand et al., 2000). This was found measuring the force between sprinters and distance runners on their first contraction interval. Results showed that overall sprinters produced greater force on first contraction than distance runners (Johansen & Quistorff, 2003). A sprinter can increase the ground force that is produced by increasing their leg strength which also causes less energy to be wasted (Mann, 1985). In sprinting, a shorter ground contact time is ideal.

Researchers have concluded that ground time is an important aspect of running. Most studies comparing different groups of runners have found that those competing in distance events have a longer ground time than sprinters. Still little information exists comparing the ground time of middle distance runners with distance runners and sprinters.

Knee and Hip Angles

Knee flexion and extension ranges affect running speed and vary between speeds. As the foot leaves the ground, (toe-off), the knee flexes through follow-through and forward swing of the gait cycle (hip flexion to maximum hip flexion) reaching maximum flexion during midswing (Milliron & Cavanagh, 1990). As foot descent occurs until foot contact, the knee angle increases in extension. At the initial foot contact until midsupport the knee may go through a slight flexion then extension from midsupport until toe-off occurs again (Mann et al., 1986; Milliron & Cavanagh, 1990). Both runners and sprinters go through similar knee movement patterns, but due to speed differences, variations occur in knee angles.

Knee angles for distance runners change based on knee position and speed. During distance running the knee joint flexes from toe-off until midstance, reaching maximal flexion. As the leg is extending from midstrike to forward swing, the knee extends with knee angles ranging from 10 degrees to 15 degrees short of full knee extension (Milliron & Cavanagh, 1990). As the velocity increases, the hip and knee angles for a distance runner increase in flexion as well as extension (Milliron & Cavanagh, 1990). During the support phase of the gait cycle, there can be a 20 degree flexion in the knee at jogging and running speeds (Mann et al., 1986). As speed increases there is an increase in motion that occurs around the knee (Mann et al., 1986; Milliron & Cavanagh, 1990).

Knee angles in sprinting vary from that of distance running. During the support phase of sprinting there was no flexion in the knee joint, unlike the 20 degree flexion that was observed at jogging and running speeds (Mann et al., 1986; Novacheck, 1998). Along with no flexion occurring, the absorption period for the knee was shorter (Novacheck, 1998). An individual going from running to sprinting had an increase in maximum knee flexion during the swing phase (Novacheck, 1998). Sprinters angles in flexion differ from distance runners due to the higher running speeds.

As the velocity increases, the maximum hip flexion also increases. When comparing different running speeds, researchers found hip flexion angles of 40 degrees in jogging, 60 degrees in running, and 80 degrees in sprinting (Mann et al., 1986). Differences in sprinters to distance runners at maximal speeds showed distance runners with an 11 degree difference in minimum hip angles compared to sprinters (Bushnell & Hunter, 2007). Sprinters displayed significantly smaller hip angles at sub-maximal and maximal speeds (Bushnell & Hunter, 2007). This increase in hip flexion leads to a longer stride length (Novacheck, 1998) and influences ground contact time.

Greater hip flexion influences the breaking forces at ground contact time (Bushnell & Hunter, 2007). As speed increases, hip flexion also increases, allowing for a faster leg recovery from swing phase to stance phase. The runner is in a better position to initiate backwards acceleration of the foot immediately before ground contact and reduce ground contact time (Kivi et al., 2002). Faster speeds influence greater hip flexion which cause faster leg recovery and reduce ground time.

Analysis comparing the differences in technique between male sprinters and distance runners found variations at a set pace of 5.81 m/s (4:37 min/mile) and a maximal speed for each athlete. Differences occurred in stride, minimum knee angles, minimum hip angles, center of mass at touchdown, and contact times (Bushnell & Hunter, 2007). These results indicate that male sprinters and distance runners display different mechanics when running at submaximal and maximal speeds.

Female runners

Biomechanical differences exist between female and male runners. When comparing male and female distance runners it was found that females running at the same velocities as males have a shorter stride length which causes a higher stride rate (Nelson, Brooks, & Pike, 1977). In addition, female runners have a greater vertical displacement of the body compared to male runners (Bransford & Howley, 1977). In sprinting, it was found that males have a longer stride length and a greater stride rate with a shorter ground contact time compared to females (Korhonen, Mero, & Suominen, 2003). These known differences indicate that the form of females differs from male runners. Results found in studies that used male participants may not produce the same findings in female runners.

Previous researchers measured aspects of form for distance, middle distance runners, and sprinters. Greater understanding of similarities in form as well as differences that exist among the three groups while running at the same paces can be studied. Additionally, research comparing female runners in varying distances is sparse.

By studying female collegiate sprinters, middle distance, and distance runners at the same speeds, variations in form can be observed. These results can aid coaches in training athletes for their maximal performance.

Chapter 3

Methods

Participants

Female middle distance runners (n = 10), distance runners (n = 10) and sprinters (n = 10) from the Brigham Young University track and cross country teams will be recruited for the study. Age of participants will range from 18 to 27 years. Colligate runners will be free of current injury to eliminate changes in form. All runners will sign an institutionally approved consent form. Runners will be informed of the procedures and possible risks and must give written consent before participating. The height (mm), weight (kg), and anterior superior iliac spine distance of each individual will be collected during data collection. In addition, left and right side measurements including leg length, anterior superior iliac spine trochanter distance, knee width, ankle width, shoulder offset, elbow width, and wrist width, and hand thickness will be recorded in mm. These measurements will help in determining joint centers from marker placements.

Instruments

Runners will be recorded running on the same treadmill in the biomechanics lab at Brigham Young University using the Vicon Nexus camera and software system (Vicon Motion Systems Ltd, Lake Forest, CA). Three dimensional movements using infrared light on cameras to read positions of moving reflective markers will be captured. Six cameras running at 75 Hz for calibration and 240 Hz for data collection will be set up at different angles. A five-point wand calibration will be performed using 5000 images. Thirty-five reflective markers will be placed on specified anatomical landmarks according to the Vicon Plugin Gait Model (Oxford Metrics). Participant measurements will allow the Vicon Nexus system to determine joint centers. All data and measurements will be collected and processed in the Vicon Nexus software system using the Vicon OLGA process (Vicon Motion Systems Ltd, Lake Forest, CA).

Procedures and Data Collection

All trials will be performed without coaches present while runners are in training season. Runners will wear racing flats (Nike® Zoom Waffle Racer™ 2005 and 2007). A five-minute warm up will be given to allow each runner to adjust to running on a treadmill. Twenty-two steps will be captured of each runner at five different running speeds. Subjects will run trials at 7.0, 8.0, 9.2, 10.9, and 13.3 mph (8:30, 7:30, 6:30, 5:30, and 4:30 per mile pace). This range of speeds will allow determination of how technique changes with increased running speed. The researcher and assistants will capture video and adjust the treadmill speed between each set with no rest between each speed.

The Vicon Nexus system determined runners knee ranges, ground contact time, center of mass separation, and stride length for each stride. The customized Excel spreadsheet (Microsoft, Redmond, Washington) calculated averages for eight steps of the data sets for each running speed and compared averages of left and right legs for the four, previously-mentioned dependent variables.

Data Analysis

Repeated measures ANOVA with speeds as the repeated measure will be used to compare differences between three groups (sprinters, middle-distance, and long distance) for each of the aforementioned dependent variables.

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Appendix B

Additional Results

Category: Sprinter

Subject 1

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.210	.180	.154	.153	.131
Left Ground Time (s)	.214	.181	.170	.150	.131
Stride Length (m)	2.278	2.605	2.860	3.175	3.428
Left Center of mass Separation (m)	.316	.280	.301	.3167	.347
Right Center of Mass Separation (m)	.292	.274	.294	.300	.362
Right Knee Range (deg)	17.8	17.375	19.0	19.4	21.0
Left Knee Range (deg)	18.9	18.9	19.0	19.1	19.4

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.329	1.520	1.674	1.852	2.000
Left Center of mass Separation (m)	.185	.164	.176	.185	.202
Right Center of Mass Separation (m)	.171	.160	.171	.175	.211

Note. All variables are averages of eight steps for each speed.

Subject 2

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.221	.190	.179	.150	.130
Left Ground Time (s)	.209	.190	.179	.160	.125
Stride Length (m)	2.089	2.333	2.560	2.864	3.213
Left Center of mass Separation (m)	.308	.321	.295	.339	.305
Right Center of Mass Separation (m)	.312	.309	.353	.348	.317
Right Knee Range (deg)	28.9	29.0	26.6	29.6	19.8
Left Knee Range (deg)	23.5	21.6	25.5	22.1	16.8

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.265	1.413	1.551	1.735	1.946
Left Center of mass Separation (m)	.187	.194	.179	.205	.185
Right Center of Mass Separation (m)	.189	.187	.214	.211	.192

Note. All variables are averages of eight steps for each speed.

Category: Sprinter

Subject 3

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.191	.219	.193	.166	.139
Left Ground Time (s)	.213	.216	.188	.150	.144
Stride Length (m)	2.098	2.435	2.715	3.010	3.375
Left Center of mass Separation (m)	.303	.310	.341	.347	.322
Right Center of Mass Separation (m)	.300	.297	.313	.276	.332
Right Knee Range (deg)	32.0	33.8	34.5	33.8	31.3
Left Knee Range (deg)	33.8	35.5	34.9	25.3	28.8

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.270	1.475	1.644	1.823	2.044
Left Center of mass Separation (m)	.184	.188	.206	.210	.195
Right Center of Mass Separation (m)	.182	.180	.189	.167	.201

Note. All variables are averages of eight steps for each speed.

Subject 4

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.218	.203	.171	.130	.111
Left Ground Time (s)	.196	.195	.166	.130	.131
Stride Length (m)	2.080	2.300	2.546	2.803	3.144
Left Center of mass Separation (m)	.312	.283	.311	.264	.327
Right Center of Mass Separation (m)	.256	.266	.292	.256	.316
Right Knee Range (deg)	31.0	26.8	28.5	18.8	25.0
Left Knee Range (deg)	25.8	26.4	27.8	21.9	24.8

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.279	1.415	1.566	1.724	1.933
Left Center of mass Separation (m)	.192	.174	.192	.162	.201
Right Center of Mass Separation (m)	.157	.164	.180	.157	.195

Note. All variables are averages of eight steps for each speed.

Category: Sprinter

Subject 5

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.173	.214	.199	.174	.150
Left Ground Time (s)	.191	.189	.210	.163	.165
Stride Length (m)	2.306	2.559	2.865	3.230	3.588
Left Center of mass Separation (m)	.254	.333	.300	.322	.346
Right Center of Mass Separation (m)	.245	.241	.302	.296	.362
Right Knee Range (deg)	20.0	29.1	23.3	24.5	26.0
Left Knee Range (deg)	19.9	19.5	26.4	23.0	26.0

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.376	1.527	1.709	1.927	2.141
Left Center of mass Separation (m)	.151	.199	.179	.192	.206
Right Center of Mass Separation (m)	.146	.144	.178	.177	.216

Note. All variables are averages of eight steps for each speed.

Subject 6

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.234	.226	.180	.181	.149
Left Ground Time (s)	.228	.214	.165	.180	.151
Stride Length (m)	2.065	2.286	2.578	2.975	3.415
Left Center of mass Separation (m)	.338	.344	.322	.388	.420
Right Center of Mass Separation (m)	.319	.329	.313	.373	.389
Right Knee Range (deg)	21.1	21.1	21.3	24.8	24.6
Left Knee Range (deg)	23.9	24.5	22.3	27.4	27.5

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.196	1.324	1.492	1.723	1.977
Left Center of mass Separation (m)	.196	.199	.186	.244	.243
Right Center of Mass Separation (m)	.185	.191	.181	.216	.225

Note. All variables are averages of eight steps for each speed.

Category: Sprinter

Subject 7

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.233	.200	.175	.156	.139
Left Ground Time (s)	.240	.199	.156	.143	.126
Stride Length (m)	2.290	2.509	2.770	3.065	3.575
Left Center of mass Separation (m)	.293	.301	.313	.332	.335
Right Center of Mass Separation (m)	.291	.284	.255	.290	.308
Right Knee Range (deg)	23.9	22.5	21.1	23.4	22.5
Left Knee Range (deg)	24.5	22.9	19.4	21.5	21.5

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.326	1.453	1.604	1.775	2.070
Left Center of mass Separation (m)	.170	.174	.182	.192	.194
Right Center of Mass Separation (m)	.168	.164	.148	.168	.178

Note. All variables are averages of eight steps for each speed.

Subject 8

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.241	.215	.200	.149	.136
Left Ground Time (s)	.219	.205	.193	.143	.130
Stride Length (m)	2.261	2.485	2.758	3.010	3.318
Left Center of mass Separation (m)	.313	.335	.354	.284	.322
Right Center of Mass Separation (m)	.311	.315	.334	.280	.334
Right Knee Range (deg)	30.9	32.1	34.0	21.8	20.9
Left Knee Range (deg)	27.5	26.5	27.4	22.3	23.6

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.349	1.483	1.645	1.796	1.979
Left Center of mass Separation (m)	.187	.200	.211	.169	.192
Right Center of Mass Separation (m)	.186	.188	.200	.167	.199

Note. All variables are averages of eight steps for each speed.

Category: Sprinter

Subject 9

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.231	.230	.201	.180	.130
Left Ground Time (s)	.221	.218	.198	.180	.140
Stride Length (m)	2.335	2.615	2.951	3.320	3.780
Left Center of mass Separation (m)	.334	.368	.368	.406	.323
Right Center of Mass Separation (m)	.297	.343	.326	.390	.312
Right Knee Range (deg)	26.0	27.5	25.8	26.4	15.8
Left Knee Range (deg)	28.9	32.0	27.8	31.3	20.5

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.352	1.514	1.709	1.922	2.189
Left Center of mass Separation (m)	.193	.213	.213	.235	.187
Right Center of Mass Separation (m)	.172	.199	.189	.226	.181

Note. All variables are averages of eight steps for each speed.

Subject 10

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.249	.225	.196	.161	.150
Left Ground Time (s)	.238	.219	.201	.164	.143
Stride Length (m)	2.331	2.651	2.978	3.393	3.830
Left Center of mass Separation (m)	.346	.339	.339	.333	.369
Right Center of Mass Separation (m)	.335	.361	.386	.343	.338
Right Knee Range (deg)	29.3	27.0	24.4	19.3	20.4
Left Knee Range (deg)	28.4	29.9	31.1	23.1	19.9

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.311	1.491	1.675	1.908	2.154
Left Center of mass Separation (m)	.194	.191	.191	.187	.208
Right Center of Mass Separation (m)	.188	.203	.217	.193	.190

Note. All variables are averages of eight steps for each speed.

Category: Middle Distance

Subject 11

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.250	.231	.236	.200	.170
Left Ground Time (s)	.290	.251	.231	.214	.170
Stride Length (m)	2.339	2.544	2.793	3.073	3.454
Left Center of mass Separation (m)	.354	.377	.408	.403	.460
Right Center of Mass Separation (m)	.368	.374	.391	.420	.436
Right Knee Range (deg)	25.4	25.5	24.5	23.1	24.4
Left Knee Range (deg)	30.8	29.4	29.9	31.5	31.3

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.315	1.431	1.571	1.728	1.942
Left Center of mass Separation (m)	.199	.212	.229	.227	.259
Right Center of Mass Separation (m)	.207	.210	.220	.236	.245

Note. All variables are averages of eight steps for each speed.

Subject 12

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.273	.249	.219	.199	.171
Left Ground Time (s)	.289	.253	.216	.189	.161
Stride Length (m)	2.295	2.499	2.801	3.085	3.421
Left Center of mass Separation (m)	.388	.394	.410	.420	.416
Right Center of Mass Separation (m)	.377	.390	.381	.388	.394
Right Knee Range (deg)	29.4	28.9	30.6	29.8	28.1
Left Knee Range (deg)	32.6	33.0	33.3	35.1	31.8

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.369	1.491	1.671	1.841	2.041
Left Center of mass Separation (m)	.232	.235	.245	.250	.248
Right Center of Mass Separation (m)	.225	.233	.227	.232	.235

Note. All variables are averages of eight steps for each speed.

Category: Middle Distance

Subject 13

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.198	.148	.150	.134	.126
Left Ground Time (s)	.200	.180	.148	.154	.109
Stride Length (m)	2.109	2.295	2.518	2.780	3.194
Left Center of mass Separation (m)	.258	.187	.290	.337	.321
Right Center of Mass Separation (m)	.293	.281	.250	.349	.308
Right Knee Range (deg)	23.9	10.8	23.3	26.0	24.0
Left Knee Range (deg)	25.8	23.0	20.3	24.9	21.9

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.239	1.348	1.479	1.633	1.876
Left Center of mass Separation (m)	.152	.110	.171	.198	.189
Right Center of Mass Separation (m)	.172	.165	.147	.205	.181

Note. All variables are averages of eight steps for each speed.

Subject 14

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.219	.211	.180	.161	.150
Left Ground Time (s)	.208	.198	.189	.151	.131
Stride Length (m)	2.278	2.536	2.853	3.193	3.609
Left Center of mass Separation (m)	.311	.338	.350	.354	.348
Right Center of Mass Separation (m)	.263	.307	.306	.298	.323
Right Knee Range (deg)	26.5	28.1	27.9	27.3	26.1
Left Knee Range (deg)	26.9	28.6	27.4	26.1	27.0

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.323	1.474	1.657	1.855	2.097
Left Center of mass Separation (m)	.181	.196	.204	.206	.202
Right Center of Mass Separation (m)	.153	.178	.178	.173	.188

Note. All variables are averages of eight steps for each speed.

Category: Middle Distance

Subject 15

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.243	.200	.175	.149	.131
Left Ground Time (s)	.223	.188	.171	.158	.130
Stride Length (m)	2.215	2.461	2.779	3.148	3.463
Left Center of mass Separation (m)	.313	.301	.280	.291	.323
Right Center of Mass Separation (m)	.296	.265	.284	.323	.291
Right Knee Range (deg)	30.4	28.3	24.1	23.9	22.1
Left Knee Range (deg)	25.0	24.6	25.1	26.4	21.1

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.316	1.462	1.651	1.870	2.057
Left Center of mass Separation (m)	.186	.179	.166	.173	.192
Right Center of Mass Separation (m)	.176	.158	.169	.192	.173

Note. All variables are averages of eight steps for each speed.

Subject 16

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.194	.198	.180	.146	.129
Left Ground Time (s)	.220	.200	.170	.159	.134
Stride Length (m)	2.158	2.365	2.583	2.828	3.188
Left Center of mass Separation (m)	.308	.317	.323	.317	.382
Right Center of Mass Separation (m)	.305	.299	.318	.330	.337
Right Knee Range (deg)	22.4	22.6	22.1	20.5	17.8
Left Knee Range (deg)	23.4	21.6	22.0	22.4	21.9

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.268	1.390	1.517	1.661	1.873
Left Center of mass Separation (m)	.181	.186	.190	.186	.225
Right Center of Mass Separation (m)	.179	.176	.187	.194	.198

Note. All variables are averages of eight steps for each speed.

Category: Middle Distance

Subject 17

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.226	.200	.190	.158	.143
Left Ground Time (s)	.210	.191	.191	.166	.139
Stride Length (m)	2.246	2.499	2.808	3.123	3.438
Left Center of mass Separation (m)	.322	.289	.329	.318	.387
Right Center of Mass Separation (m)	.300	.288	.315	.345	.320
Right Knee Range (deg)	25.5	23.4	24.5	21.1	26.8
Left Knee Range (deg)	29.4	29.0	31.8	30.4	27.3

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.320	1.468	1.650	1.835	2.020
Left Center of mass Separation (m)	.189	.170	.193	.187	.228
Right Center of Mass Separation (m)	.176	.169	.185	.203	.188

Note. All variables are averages of eight steps for each speed.

Subject 18

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.240	.225	.218	.184	.171
Left Ground Time (s)	.224	.228	.200	.183	.154
Stride Length (m)	2.264	2.504	2.791	3.083	3.463
Left Center of mass Separation (m)	.320	.342	.360	.387	.428
Right Center of Mass Separation (m)	.328	.345	.364	.388	.422
Right Knee Range (deg)	27.5	28.3	28.5	27.4	29.0
Left Knee Range (deg)	27.0	27.8	27.3	26.4	26.8

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.351	1.494	1.665	1.839	2.066
Left Center of mass Separation (m)	.191	.204	.215	.231	.255
Right Center of Mass Separation (m)	.196	.206	.217	.231	.252

Note. All variables are averages of eight steps for each speed.

Category: Middle Distance

Subject 19

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.251	.224	.200	.166	.140
Left Ground Time (s)	.268	.230	.199	.166	.140
Stride Length (m)	2.115	2.363	2.658	3.050	3.416
Left Center of mass Separation (m)	.359	.349	.348	.348	.316
Right Center of Mass Separation (m)	.351	.358	.324	.333	.303
Right Knee Range (deg)	30.8	28.4	29.0	28.5	21.1
Left Knee Range (deg)	23.8	24.6	24.5	25.3	19.3

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.262	1.410	1.586	1.820	2.038
Left Center of mass Separation (m)	.214	.208	.208	.207	.189
Right Center of Mass Separation (m)	.209	.214	.193	.199	.181

Note. All variables are averages of eight steps for each speed.

Subject 20

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.229	.198	.190	.150	.141
Left Ground Time (s)	.229	.208	.191	.163	.150
Stride Length (m)	2.326	2.570	2.889	3.225	3.650
Left Center of mass Separation (m)	.324	.323	.342	.368	.397
Right Center of Mass Separation (m)	.332	.321	.318	.386	.410
Right Knee Range (deg)	24.3	22.4	22.5	22.5	23.4
Left Knee Range (deg)	26.3	22.5	20.5	24.6	23.5

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.290	1.425	1.602	1.789	2.024
Left Center of mass Separation (m)	.179	.179	.190	.204	.220
Right Center of Mass Separation (m)	.184	.178	.176	.214	.227

Note. All variables are averages of eight steps for each speed.

Category: Distance

Subject 21

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.249	.240	.211	.188	.173
Left Ground Time (s)	.268	.233	.223	.190	.171
Stride Length (m)	2.110	2.314	2.499	2.763	2.963
Left Center of mass Separation (m)	.333	.366	.373	.411	.408
Right Center of Mass Separation (m)	.324	.353	.383	.393	.426
Right Knee Range (deg)	27.0	29.9	30.0	31.4	28.8
Left Knee Range (deg)	27.6	30.0	32.9	31.8	32.8

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.298	1.423	1.537	1.699	1.822
Left Center of mass Separation (m)	.205	.225	.229	.253	.251
Right Center of Mass Separation (m)	.199	.217	.236	.242	.262

Note. All variables are averages of eight steps for each speed.

Subject 22

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.261	.233	.229	.215	.164
Left Ground Time (s)	.278	.233	.213	.201	.174
Stride Length (m)	2.298	2.506	2.790	3.020	3.239
Left Center of mass Separation (m)	.368	.370	.393	.352	.408
Right Center of Mass Separation (m)	.373	.371	.375	.364	.440
Right Knee Range (deg)	30.8	30.0	29.6	32.4	26.6
Left Knee Range (deg)	31.8	30.5	31.0	34.9	29.3

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.350	1.473	1.639	1.774	1.903
Left Center of mass Separation (m)	.216	.217	.231	.207	.239
Right Center of Mass Separation (m)	.219	.218	.220	.214	.258

Note. All variables are averages of eight steps for each speed.

Category: Distance

Subject 23

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.294	.279	.223	.210	.194
Left Ground Time (s)	.266	.254	.223	.204	.170
Stride Length (m)	2.278	2.549	2.859	3.185	3.588
Left Center of mass Separation (m)	.352	.400	.364	.410	.462
Right Center of Mass Separation (m)	.313	.345	.346	.420	.436
Right Knee Range (deg)	33.0	38.8	36.6	40.3	43.9
Left Knee Range (deg)	26.0	26.8	31.8	36.9	31.8

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.359	1.521	1.706	1.900	2.141
Left Center of mass Separation (m)	.210	.239	.217	.244	.276
Right Center of Mass Separation (m)	.186	.206	.206	.251	.260

Note. All variables are averages of eight steps for each speed.

Subject 24

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.244	.226	.190	.179	.156
Left Ground Time (s)	.250	.259	.200	.160	.149
Stride Length (m)	2.211	2.455	2.676	2.915	3.229
Left Center of mass Separation (m)	.355	.384	.333	.375	.391
Right Center of Mass Separation (m)	.373	.422	.354	.333	.409
Right Knee Range (deg)	28.3	29.9	23.8	25.9	25.3
Left Knee Range (deg)	31.6	33.6	28.0	24.6	28.5

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.286	1.427	1.556	1.695	1.877
Left Center of mass Separation (m)	.207	.223	.193	.218	.227
Right Center of Mass Separation (m)	.217	.245	.206	.194	.238

Note. All variables are averages of eight steps for each speed.

Category: Distance

Subject 25

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.229	.225	.200	.169	.156
Left Ground Time (s)	.228	.219	.211	.191	.150
Stride Length (m)	2.271	2.524	2.834	3.173	3.459
Left Center of mass Separation (m)	.328	.364	.368	.380	.416
Right Center of Mass Separation (m)	.312	.357	.374	.402	.387
Right Knee Range (deg)	37.9	43.1	41.4	42.6	40.0
Left Knee Range (deg)	35.0	42.3	43.0	44.1	35.8

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.442	1.602	1.799	2.014	2.196
Left Center of mass Separation (m)	.208	.231	.234	.242	.264
Right Center of Mass Separation (m)	.198	.227	.238	.255	.246

Note. All variables are averages of eight steps for each speed.

Subject 26

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.251	.208	.201	.183	.159
Left Ground Time (s)	.234	.205	.185	.188	.149
Stride Length (m)	2.040	2.276	2.593	2.920	3.303
Left Center of mass Separation (m)	.311	.288	.357	.373	.397
Right Center of Mass Separation (m)	.292	.317	.326	.371	.355
Right Knee Range (deg)	25.5	22.1	29.1	29.5	26.1
Left Knee Range (deg)	22.3	16.3	25.4	26.3	23.0

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.199	1.337	1.523	1.716	1.940
Left Center of mass Separation (m)	.183	.169	.210	.219	.233
Right Center of Mass Separation (m)	.171	.186	.192	.218	.209

Note. All variables are averages of eight steps for each speed.

Category: Distance

Subject 27

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.245	.218	.209	.186	.16
Left Ground Time (s)	.228	.234	.216	.190	.158
Stride Length (m)	2.204	2.439	2.721	3.058	3.463
Left Center of mass Separation (m)	.341	.344	.371	.400	.423
Right Center of Mass Separation (m)	.328	.381	.404	.413	.414
Right Knee Range (deg)	32.5	32.8	33.5	34.9	34.0
Left Knee Range (deg)	28.9	32.6	34.1	29.0	30.4

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.276	1.412	1.576	1.770	2.005
Left Center of mass Separation (m)	.197	.199	.215	.231	.245
Right Center of Mass Separation (m)	.190	.221	.234	.239	.239

Note. All variables are averages of eight steps for each speed.

Subject 28

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.231	.209	.191	.166	.145
Left Ground Time (s)	.224	.220	.209	.171	.149
Stride Length (m)	2.065	2.308	2.571	2.815	3.216
Left Center of mass Separation (m)	.301	.298	.347	.363	.374
Right Center of Mass Separation (m)	.321	.270	.334	.316	.350
Right Knee Range (deg)	30.8	29.0	36.4	36.5	36.3
Left Knee Range (deg)	33.5	23.8	33.3	28.6	31.0

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.196	1.336	1.489	1.630	1.862
Left Center of mass Separation (m)	.174	.173	.201	.210	.216
Right Center of Mass Separation (m)	.186	.156	.193	.183	.203

Note. All variables are averages of eight steps for each speed.

Category: Distance

Subject 29

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.274	.244	.223	.204	.176
Left Ground Time (s)	.279	.241	.230	.199	.173
Stride Length (m)	2.125	2.321	2.575	2.850	3.085
Left Center of mass Separation (m)	.489	.382	.416	.427	.428
Right Center of Mass Separation (m)	.496	.373	.393	.416	.423
Right Knee Range (deg)	52.3	33.1	35.0	32.0	27.5
Left Knee Range (deg)	58.4	32.9	33.9	33.9	31.6

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.268	1.385	1.536	1.700	1.841
Left Center of mass Separation (m)	.292	.228	.248	.254	.255
Right Center of Mass Separation (m)	.296	.223	.235	.248	.252

Note. All variables are averages of eight steps for each speed.

Subject 30

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Right Ground Time (s)	.270	.241	.246	.215	.180
Left Ground Time (s)	.275	.241	.223	.209	.183
Stride Length (m)	2.289	2.491	2.748	3.128	3.495
Left Center of mass Separation (m)	.351	.375	.412	.432	.453
Right Center of Mass Separation (m)	.328	.362	.384	.423	.424
Right Knee Range (deg)	29.5	29.1	30.8	31.1	29.4
Left Knee Range (deg)	28.1	29.0	27.4	30.4	26.8

Variables with height factored out

Speed (m/s)	3.17	3.58	4.11	4.87	5.94
Stride Length (m)	1.269	1.382	1.524	1.735	1.938
Left Center of mass Separation (m)	.194	.208	.228	.239	.251
Right Center of Mass Separation (m)	.182	.201	.213	.235	.235

Note. All variables are averages of eight steps for each speed.