3D COACHING: SPORTS BIOMECHANICAL ANALYSIS OF COLLEGIATE ATHLETICS (*TRACK & FIELD*)

by

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A DISSERTATION

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DISSERTATION ABSTRACT

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Athletic (*Track & Field*) championships have showcased globally the great strength, power, and speed of athletes in a myriad of disciplines. Notably over the last 30 years, steady improvements in championship performances have intrigued the Athletics community—athletes, coaches, spectators—sparking interest to look further into how this caliber of athletes perform and what the training demands are to continue the pace of progress.

Coaches, by nature, focus on what is familiar to them until the next ‘phenomenon’ in development and training becomes recognizable. In consequence, sports science research sources are perceived with complexity, and unused or misused by the Athletic community. Efforts led by leading sports scientists have been made in the live capture of world-class competitors during world championships to better understand, discuss, and use science within the current state of Athletics in published biomechanical reports.

Although athletes have a critical role in whether achievements are met, coaching efforts are to serve the athlete's needs within the demands of each discipline. Balancing what an athlete can do biomechanically and the mechanism within a discipline is the challenge. Coaches often turn to the experiences that have built their coaching philosophy

for guidance on the best approaches. With a focus on the NCAA collegiate championship, this project served as a biomechanical-driven evidence-based collection to better understand championship performance. The results justified achieving season-best sprint times and jump marks for higher seeding purposes. Furthermore, results underscored the high individuality in step characteristics during the development of acceleration and velocity of sprinters and jumpers.

NCAA championships feature arguably the best collegiate and world-class competitors in Athletics. When the coaching and scientific views are taken into consideration at this level, an improved attempt at defining and appropriately applying mechanical principles to the technique and skills used can be established. Assessing kinematic parameters captured during these championships provides insight into biomechanical contributions in performances for coaches to evaluate and improve training design that will shape an athlete's performance. An opportunity is available to add to the sports science narratives on the mechanics of Athletic disciplines using a biomechanics lens to magnify the coaches' eye.

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From lessons learned, I came to form my own coaching style and philosophy applied in a myriad of coaching roles. I'd like to thank the athletes, especially UO Track & Field athletes, whom I have had a chance to coach, connect with, and watch grow into more than they ever imagined. Although tough on them with expectations, I appreciate those who were coachable, contributors, and committed to trusting in the process of learning their craft, thus becoming men and women of character beyond the field of play.

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Dedicated to whom I know best.
'Learn from the Learner'
'…allow passion to become part of your purpose…'

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INTRODUCTION

1.1 CONTEXT

Derived from the Greek word's bios and mēchanikē, meaning 'life' and 'mechanics', the field of biomechanics has been used to describe movement and associated mechanics in several sports forums (Yeadon & Challis, 1994). Athletics, also known to many as *Track & Field*, displays a myriad of speeds, heights, and release methods measured and timed in a contested space. Sports biomechanics have been used for over 30 years in the sport of Athletics (*Track & Field*) by World Athletics to discuss mechanics, make comparisons, direct training measures, and ultimately improve performance (World Athletics, 2018).

The history of Athletics shows how the sports' disciplines have progressed in technique and skill based on achieved performance results. With this evolution, it can be inferred members of the Athletic community—athletes, coaches, spectators—have acclimated to the sport's advances according to their respective capacities. This suggests coaches and scientists have held different approaches to development and applicable understanding of sports performances, and this lack of integration has perhaps wasted some unapplied knowledge painstakingly acquired.

1.2 COACHING VIEW

The coach's view comes in many forms where belief is often formed by how they were trained, how they were mentored, and how they interact with coaching colleagues. From these support pillars, one can conclude a perceived understanding of training, training design, and training implementation is built within coaching eventually solidifying into a coaching philosophy. Practices reflecting the philosophy of a coach are intended to assist an athlete in their preparation for competition. The athlete prepares for competition using a set of drills and practices materialized from the coach's philosophy.

To the author as a well-experienced and current Athletics coach, it can be inferred that coaches look to use specific strength exercises and drills to direct and improve the habits and strengths in Athletic discipline based on what they would like to see from their athletes in training and later in competition. The value a coach places on an exercise or drill they have explored with, or experienced, suggests it is based on their subjective impression of the effectiveness it shows in training and/or competition. One can speculate the periods and ways in which coaches evaluate this effectiveness is what makes coaching unique in the sport of Athletics. This suggests an understanding of certain biomechanical principles is commonly picked and chosen by many coaches, while others take a general or small interest in what sports science research may reveal about Athletic disciplines. A large or small interest in sports science research should lead coaches to use research in gaining perspective into what Athletic disciplines demand, its associated indicators, and proper application of findings toward effective training within the potential profile of their athletes.

1.3 SCIENTIST VIEW

The scientific view also comes in multiple forms when examining Athletic performance. It can be inferred that scientists often engage in study practices originating from previous research design, advisor research interests, or by assisting ongoing studies in their field. This suggests novel approaches are taken in an attempt to understand long-mysterious biomechanical principles as a result of shifts in research design and technology. Pilot work is then designed to acquire novel data into long-obscured biomechanical facets of performance. From these works, experience in biomechanics builds and sets scientists to assess the human body's attempt at movement (Mann, 1986).

One can also conclude scientists regularly consider how published information appears and is understood by the community of fellow researchers who judge the relevance of their work. Whether extensive consideration is taken as to what and how effective research findings may appear outside the biomechanics field, the key for scientists is to deduce data findings objectively, communicate practical research significance, and simplify the complexity of science to show how useful it can be in examining Athletic disciplines.

Scientists have found difficulties in funding biomechanical sports performance studies due to the magnitude of the projects and assistance needed to conduct such research work (Knudson, 2021). This suggests there is concern about assembling a team of scientists for the next project and being supported by grant applications based on government-directed efforts in health and wellness.

1.4 EVIDENCE-BASED VIEW

Scientists within scientific disciplines are challenged in having their published work consumed and applied by the applied professionals in their respective fields. Researchers have stated the gap between knowledge generation and knowledge use, or application, remains problematic based on no immediacy of professionals following a researcher’s path with a ‘good idea’ (Backet, 1988; Johnson et al., 1996; Faulkner et al., 2006). Lack of results and perception of evidence have been offered as explanations for the gap between what is known and what is practiced (Faulkner & Biddle, 2001; Faulkner et al., 2006). To clarify research processes and effectiveness, scientists have placed efforts into creating and developing evidence-based practices.

Faulkner et al. (2006) and Knudson (2021) address exercise and sports scientists being faced with the need to demonstrate their work based on sound evidence ready to impact professional practices and policies. For example, the sciences—fields of medicine, kinesiology, and biomechanics—have looked to adopt evidence-based practices designed to critically review the literature to implement the most effective practices of evaluation.

The medical field views the practice of evidence-based medicine as an opportunity to integrate individual clinical expertise with the best available external clinical evidence from systematic research with the patient’s treatment preference (Sackett, 1996). The kinesiology field regards evidence-based practices as elevating the coexistence of quality applied and theoretical research, encouraging interdisciplinary research, and providing integrated and accessible research summaries (Knudson, 2005; Knudson, 2021).

Specifically, biomechanics explores evidence-based practices in case studies for coaches to consider in modifying and improving movement (Coutts, 2017; Knudson, 2021). In reviewing running kinematics as an important role in injuries, Souza concluded systematic video-based biomechanical analysis rooted in current evidence on running injuries supported treatment strategies to be developed by clinicians (Souza, 2016). Based on these approaches, using evidence-based practices used in sports performance is applicable.

Part of sports performance is the appropriate translation and utilization of technique and training components at a high level. The goal behind athlete-centered research is to be translated into practice to inform the development and improvement of athlete preparation and/or performance (Coutts, 2017). Evidence-based practices in high-performance sports may provide a balance between benefits and risks in decision-making, challenge belief-based views, and integrate athlete and coach preferences in how training and performance are approached (Coutts, 2016; Coutts, 2017; Slattery et al., 2021). Therefore, evidence-based practices in sports performance ultimately rely on what is known in the literature, what works best in the coach's hand, and what the preferences of the athlete are.

A collaborative effort towards translating, integrating, and utilizing sports science with sports performance can be made through evidence-based innovative, iterative processes. Publications associated with various science societies as part of their mission encourage applied science. Such reviews have been featured in the National Strength and Conditioning Association (NSCA), Strength & Conditioning Research (SCJ), American College of Sports Medicine (ACSM) Journals, Journal of Sports Physiology and

Performance (IJSPP), American Academy of Kinesiology and Physical Education (AAKPE), and International Society of Biomechanics in Sports (Knudson, 2005; Coutts, 2017; Knudson, 2021; Slattery et al, 2021). Publications are given context to what Slattery et al. (2021) calls the sport-science impact matrix. It is divided into two components, the continuum of expertise and the continuum of the environment.

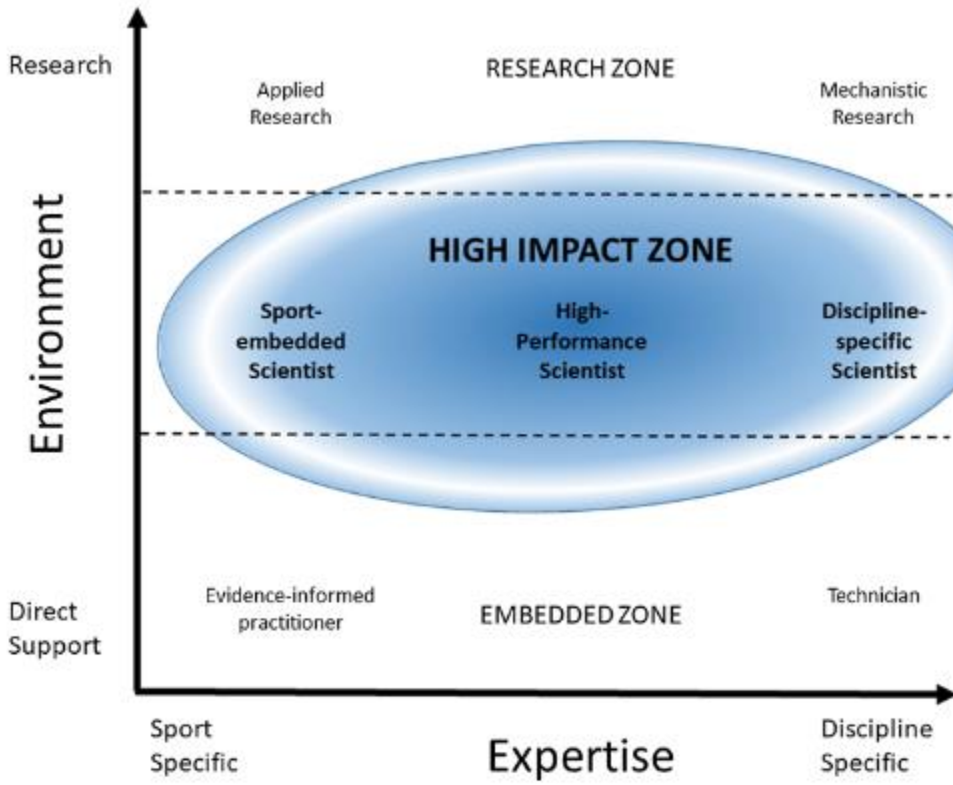


Figure 1.1. The sport-science impact matrix (*reproduced with permission from Slattery et al., 2021*).

On the x-axis, the expertise continuum is the range of specific (sport to discipline) knowledge of the scientist, while the y-axis represents the setting (environment) in an individual (direct to research) that affects sports performance (Slattery et al., 2021). The question scientists should ask more often centers around where their work sits within the matrix (Slattery et al., 2021). Answering this question may condition scientists to evaluate three qualities of their work—its contribution, interpretation, and application. Slattery et al. (2021) state an understanding of how studies contribute to improving sports performance assists readers to then understand the scientific perspective to interpret and apply research findings. It can be inferred that describing the research environment along with how findings can be applied to the area of practice is reasonable (Faulkner et al., 2006; Slattery et al., 2021).

Although there is value in having research conducted in the practice and/or competition arena, there is efficacy in closely simulated or lab-oriented research environments as well. Laboratory (lab) studies have played an important role in providing a base for developing evidence-based practices for high-level sports performance (Coutts, 2017). For example, on a controlled indoor track embedded with force platforms, Bezodis et al. (2021) aimed to compare the effects of calculating step-averaged reaction forces with three calculation methods between male sprinters by analyzing the initial push-off step out of standing start and starting blocks, particularly during late stance as the acceleration phase progressed. Salo and Grimshaw (1998) investigated variation sources and kinematic variability of video motion analysis in sprint hurdles, showing one operator and analysis system together produced repeatable values for most variables. Graham-Smith and Lees (2004) went on to conduct a three-dimensional analysis of the touch-down to take-off phase in the long jump and explore the interrelationships between key variables; they determined variables important to performance are interdependent and can only be identified by using appropriate statistical techniques. It is unknown to what degree integration of statistical techniques have been added to coaching philosophies and subsequently, instruction of Athletic disciplines. From authors Bezodis to Salo, before and after, biomechanists have explored the ‘science’ behind Athletic disciplines for decades in ways where the perception and perspective of sports performance are challenged.

The impact of these challenges should be managed within research and sports environments. Researchers acknowledge research is routinely achieved through “slow and deliberate” lab work, whereas the sports field is commonly achieved through a “fast-paced” mode in training and competition settings (Slattery et al., 2021; Coutts, 2016). Although appearing to have opposing roles, the appropriate implementation and application of both can serve to inform on the development and improvements made in training and competition. World Athletics (WA, formerly the IAAF, International Association of Athletics Federation), the sport governing body for Athletics has supported recent research endeavors (World Athletics, 2018; World Athletics, 2019), which suggest unprecedented insights have been delivered on interpreting the performance of various Athletic disciplines during World Championship competition.

1.5 INVESTIGATIONS OF ATHLETICS (*TRACK & FIELD*)

Insights into Athletics invite coaches and sports scientists to re-examine techniques and mechanisms that underpin performance. The process of examining these components in sports includes marking what implications measurable variables say about performance. Informing on the development and improvement of athletes which aligns with coaching priorities and moving the sport forward is the goal.

Over the last three decades, Athletic competition at the highest level, the World Championships, has been biomechanically investigated. World Athletics (WA) have been the leaders in conducting Athletic competition research and disseminating their report findings. To the authors' knowledge, the investigation of major Athletic competitions held in the United States has primarily studied kinematic parameters, motions of the body without regard to the forces that develop these motions, for sprint and jump disciplines. Termed the Elite Athletic Project, select Olympic caliber men (n > 15) and women (n > 20) sprinters from the 100-m to 400-m discipline, were filmed in five top-level competitions during the 1982 and 1983 outdoor seasons (Mann et al., 1982). The purpose of the project was to provide feedback on athlete strengths, weaknesses, and potential areas of performance improvement based on critical kinematic data (Mann et al., 1982). Of the variable (e.g., stride rate, stride length, total body vertical speed, arm motion) results reported, researchers reported sprint running was dominated by the production of maximum horizontal body speed utilizing strength and proper movement mechanics (Mann et al., 1982). One can conclude coaches may have integrated some findings based on continued athlete improvement trends, observed technique styles, and major championship showings in Athletic disciplines.

Investigations continued at the 1984 Los Angeles Summer Olympic Games of all track running disciplines. Specifically, the men's 200-m finalists were singled out for initial analysis in which select direct performance variables (e.g., body velocity, step rate) and upper and lower kinematics (e.g., upper arm position, lower leg velocity) were taken (Mann & Herman, 1985). The study demonstrated the success of the best performers was attributed to eight factors: 1) higher horizontal velocity; 2) greater stride rate; 3) shorter support time; 4) large upper leg angle at takeoff; 5) higher upper leg velocity during support; 6) higher lower leg velocity at touchdown; 7) smaller foot to body touchdown distance; and 8) higher relative foot velocity at touchdown (Mann & Herman, 1985). Interestingly, a 2010 study by Salo and co-authors discovered in their analysis of 52 male elite-level 100-m races from publicly televised broadcasts (Olympic, World, European, and IAAF Grand Prix series championships), a large variation of performance patterns with step rate (SR) and step length (SL) reliance to be a highly individual occurrence (Salo et al., 2010).

Branching off as the successor of the Elite Athlete Project, the Scientific Services Program, recorded the performances of select elite female (n = 14) and elite male (n = 14) jumpers (Hay, 1988). Film records of at least three trials in one competition meet were deemed suitable for analysis as select variables (e.g., step length, step rate) of the last four strides into the take-board were taken (Hay, 1988). Based on previous findings by Lee et al. (1982), jumpers did adopt a visual control strategy during the final steps of the approach; little suggested the adopted visual control strategy related to the magnitude of error in stride accuracy; a toe-board distance of 0.20-m or less was very good; coach's checkmark may be better served at the fifth to sixth stride from the board; and 67% of total adjustments were made in last two strides to correct prior stride errors (Hay, 1988).

Each kinematic study above used high-speed cameras to film sagittal positions to gain a better understanding of the select parameters and what implications exist regarding the performance of track (sprints) and field (horizontal jumps) disciplines (Mann & Herman, 1985; Hay, 1988; Mann et al., 1982). Kinematic studies have been utilized to accurately quantify the motions of the body or limbs involved in sprinting and jumping, but the causes of those motions. Kinetic studies, on the other hand, are those which measure the forces of movement, quantify ground reaction forces (GRFs), and through embedded coordinate axes and inverse dynamics calculations reveal how joint moments and joint powers contribute to movement (Davis et al., 1991; Kadaba et al., 1989). It can be inferred that kinematics are more docile to study in situ in a competition where cameras can be placed around performance areas to capture movements without disruption with high ecological validity of disciplines.

Kinetic studies have been less frequent in scientific literature, in part, due to expense and disruption to the competition area needed for specialized equipment being embedded into its surface. Kinetic descriptions were used to describe work done during running (Fenn, 1930; Mann, 1981; Mann, 1983), including muscle moments generated by joints (Elftman, 1940; Mann, 1981; Mann, 1983). This work was performed in laboratory settings and not actual competition settings using subjects described as trained runners (Elftman, 1940) and highly skilled sprinters ranging from collegiate to world-class (Mann, 1981; Mann, 1983). Further descriptions were done by Plagenhoef presenting lower limb moments generated in distance running (Plagenhoef, 1968; Mann, 1981;

Mann, 1983). Diving more into sprinting, Mann focused his efforts on the biomechanical analysis of sprinting. A comprehensive investigation and description of sprint kinetics were completed using muscle moments generated as the primary descriptive variable (Mann, 1981). Footage of 15 collegiate to world-class sprinters was taken using sagittal plane views with high-speed cameras and the vertical and horizontal force components were captured using force platforms (Mann, 1981). He concluded the better sprinters succeeded in minimizing horizontal braking force with larger hip extensor and knee flexor impulses and utilized the entire ground phase to generate productive moment, while less skilled sprinters terminated their moment production prematurely or began their leg recovery action before toe-off (Mann, 1981). Although the above study findings became known, measuring specific lower limb joint kinetics on sprint performance fundamentals was not known.

During the sprint push-off, Charalambous et al. (2012) quantified and explained lower limb joint moments and mechanical powers, and ankle stiffness. Study results showed profound disparities in hip and knee kinetics and that ankle stiffness had a positive impact on vertical velocity but not horizontal velocity, thus providing an understanding of sprint push-off technique depending on the phase of a sprint stance (Charalambous et al., 2012). Along with identifying joint moments and joint stiffness in sprint performance, other studies went on to describe kinetic variable relationships.

To determine the relationships of force-velocity (FV), power-velocity (PV), and mechanical effectiveness of force application during sprint running, Samozino et al. (2015) used a simple field method that estimated the step-averaged GRFs of nine elite or sub-elite sprinters during overground sprint accelerations. Researchers proposed quantifying mechanical effectiveness would aid in distinguishing the inter- or intra-individual differences in both FV and PV mechanical profiles and sprint performances, thus becoming useful in orienting training (Samozino et al, 2015). High validity was found in the proposed simple method in determining power, force, velocity, and mechanical effectiveness as key kinetic factors related to sprint running (Samozino et al, 2015). To test the criterion validity of the simple method, Morin et al. (2019) went on to replicate Samozino et al. (2016) study by using 16 male-trained sprinters performing 60-m sprints over force platforms embedded under track surface. It was found that the simple method could accurately estimate sprint acceleration kinetics when implemented correctly (Morin et al., 2019).

Based on Morin et al. (2019) recent discoveries, it can be inferred that scientific investigations have intrigued coaches and scientists to delve further into what contributes to sprinting and how sprinting contributes to Athletic disciplines. Performance results over the last 30 years suggest coaches have attempted to integrate these findings within technical instruction for preparation in competition.

Intrinsically, studies on elite sprint and jump athletes have evolved from simple kinematic descriptions within disciplines to more progressive advanced kinematic and kinetic comparisons between elite and non-elite caliber athletes (Mann, 1983; Mann, 1992). This has led global coaches and scientists in recent years to engage in projects dedicated to capturing competition condition data. These efforts have been dominated and spearheaded by the World Athletics (WA) mission.

Outside of the Olympic Games, the World Championships is the highest level of competition available for Athletic world-class athletes to compete in for a chance to be crowned the fastest sprinter and farther jumper. The 1983 historic results from the first Athletics World Championships held in Finland (e.g., Carl Lewis, gold medal 100-m and long jump) (World Athletics, 2023), prompted the IAAF (predecessor of WA) to ask "…what coach or aspiring athlete would not profit by being present at a major athletics meeting…?" (Brüggemann & Sušanka, 1990). The federation deemed coaches and athletes able to observe the actions and techniques of the finest athletes would be an invaluable aid to performance improvement and the development of future champions (Brüggemann & Sušanka, 1990). IAAF also acknowledged practical knowledge for coaches and athletes was not automatic and expressed that the nature of championship settings (number of athletes, speed of movements, emotions of competition, and spectators) make detailed and useful observations difficult (Brüggemann & Sušanka, 1990). The II World Championship marked the IAAF's first attempt to address those unable to attend the meet, improve performance, and inform on the development of discipline techniques for future champions in a sports scientific project.

The International Athletic Foundation Scientific Project on the 1987 II World Championships in Rome functioned to provide an understandable record and analysis for coaches and athletes to use and apply to practice settings to improve performance but also increased the channels of communication between coaches and scientists (Brüggemann & Sušanka, 1990). Recordings of competition discipline rounds offered coaches and athletes an opportunity to recap and observe what occurred and/or changed from round to round. The identification and evaluation of factors of performance—reaction time, acceleration, maximum speed, speed endurance, approach, take-off, flight, landing—drew conclusions coaches and athletes could use as possible unequivocal reasons for final performance times (100-m) and marks (long jump) achieved.

For the 100-m, a combined male & female biomechanical report presented some key notes and findings:

- reaction time in the highest events of the best athletes was less than 0.200 m/s in 95% of official results; final performance time is more strictly influenced by the acceleration capacity for women than it is by men; high maximum running speed is what creates an outstanding performance; inferior sprinters reach a maximum speed peak that drops fairly steeply whereas an elite sprinter loses maximum speed slowly; comparison of women finalists time through qualifying rounds showed a high degree of stability of acceleration speed; men finalists (Lewis & Johnson) achieved highest mean velocity from 80 – 90-m and 50 – 60-m, respectively (Brüggemann & Sušanka, 1990).

For the long jump, a combined male & female biomechanical report presented some key notes and findings:

- marked improvement in best jumps among the women; flight distance (defined as the horizontal distance the CM travels during the flight phase while an athlete is in the air (Hay, 1986; Hay et al., 1986; Brüggemann & Sušanka, 1990) was a dominant parameter in its percentage contribution to the official distance for both genders; the approach of both genders determines the initial velocities at touchdown; for men, the precision of the approach was very exact based on the eight best long jumpers; horizontal velocity at the instance of takeoff in last four steps indicated a variation of take-off velocity being susceptible to rhythmic changes for all men and most women; and variations of stride length plays a role in modulating the center of mass (CM)'s velocity during the take-off preparation phase (Brüggemann & Sušanka, 1990).

This biomechanical project on Rome's World Championship set out to gain a scientific understanding of the 100-m and long jump and assist athletes and coaches in preparation for future competitions (Brüggemann & Sušanka, 1990). Supporting the sport of Athletics in this manner inevitably brought on discussions about the next project and potential contributions. The IAAF continued to sponsor a series of biomechanical research projects on proceeding World Championships to push forward part of their mission in advancing athletes, coaches, and the sport of Athletics with new and updated measurement techniques.

As of recent, efforts towards their mission manifested themselves in the most extensive biomechanical projects done to date during the 2017 London World Championships and 2018 Birmingham Indoor World Championships (*Note: For the purposes of this project, outdoor championships will be the emphasis of interest*). Published reports from these championships were subsequently released exhibiting the technological advancements made in data capture, progression in signature Athletic disciplines, and the interpretation of performance data. Scientists, in the 1987 Rome World Championships, for the long jump, used high-speed cameras to provide three-dimensional analysis of the last four strides into the board, the take-off, flight, and landing; panned cameras in a horizontal plane; and synchronized cameras externally (Brüggemann & Sušanka, 1990). In the same championship for the 100-m, time synchronization, and high-speed cameras in select locations to enable three-dimensional analysis were used.

Diagrammed below are camera positions and locations of 100-m in the 1987 World Championships (*Note: Camera location for the long jump was not available*).

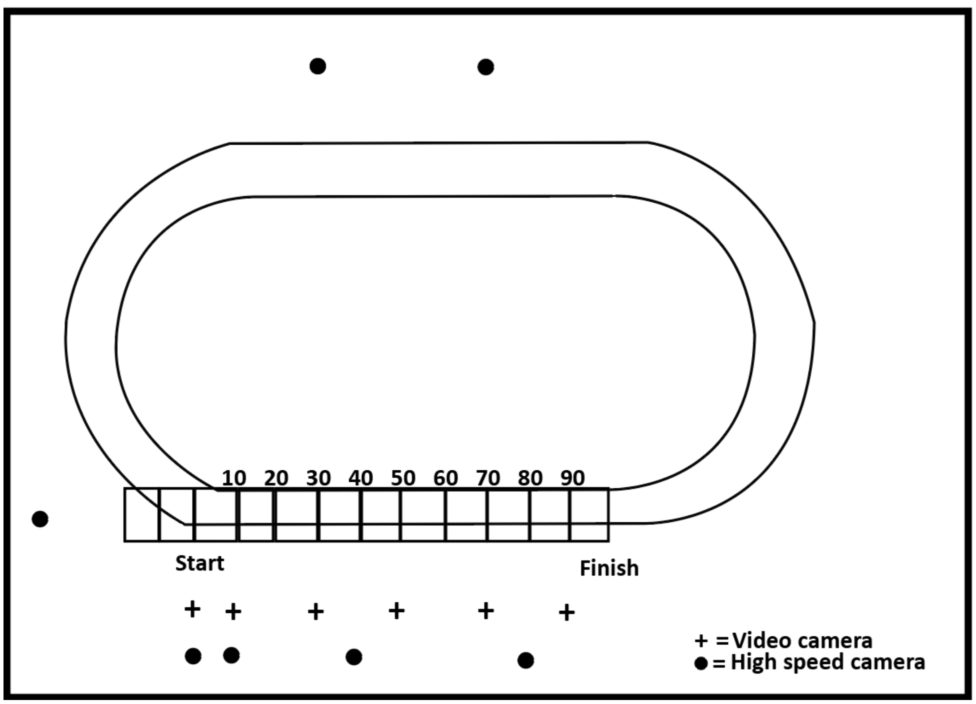


Figure 1.2. WA World Championships Rome 1987 Women's 100-m finals. Shown are the camera layout and location indicated by '+' and dots' from the published 1987 biomechanical report (*adapted from Brüggemann & Sušanka, 1990*).

Held 30 years later, the 2017 World Championships (WC) used select vantage locations for camera placement for the 100-m and long jump, along with enhanced cameras, calibration procedures, synchronization techniques, three-dimensional coordinate algorithms, and reliability processes (Bissas et al., 2018a; Bissas et al., 2018b; Tucker, et al., 2018a; Tucker, et al., 2018b).

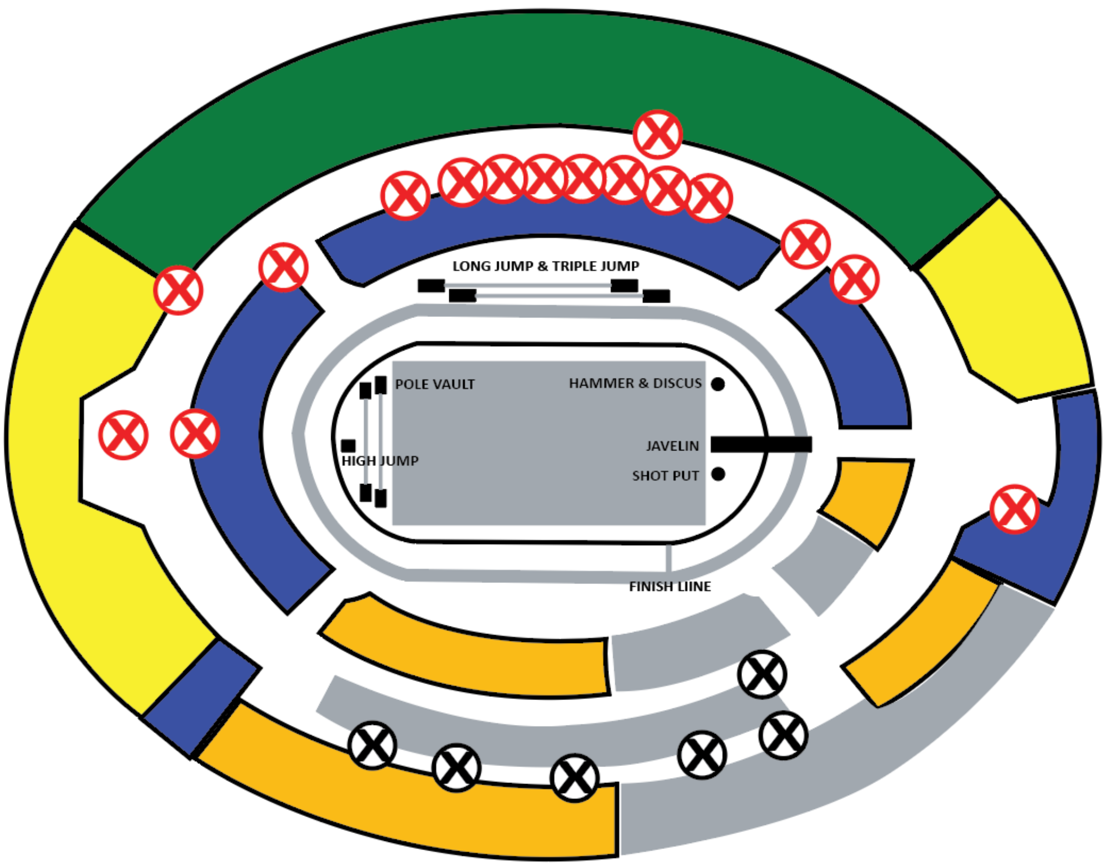


Figure 1.3. WA World Championships London 2017 Men's and Women's 100-m finals. Illustrated are the camera layout and locations chosen by black and white-filled circles vs non-selected locations indicated by white and red X-filled circles, from the published 2017 biomechanical reports (*adapted from Bissas et al., 2018a; Bissas et al., 2018b*).

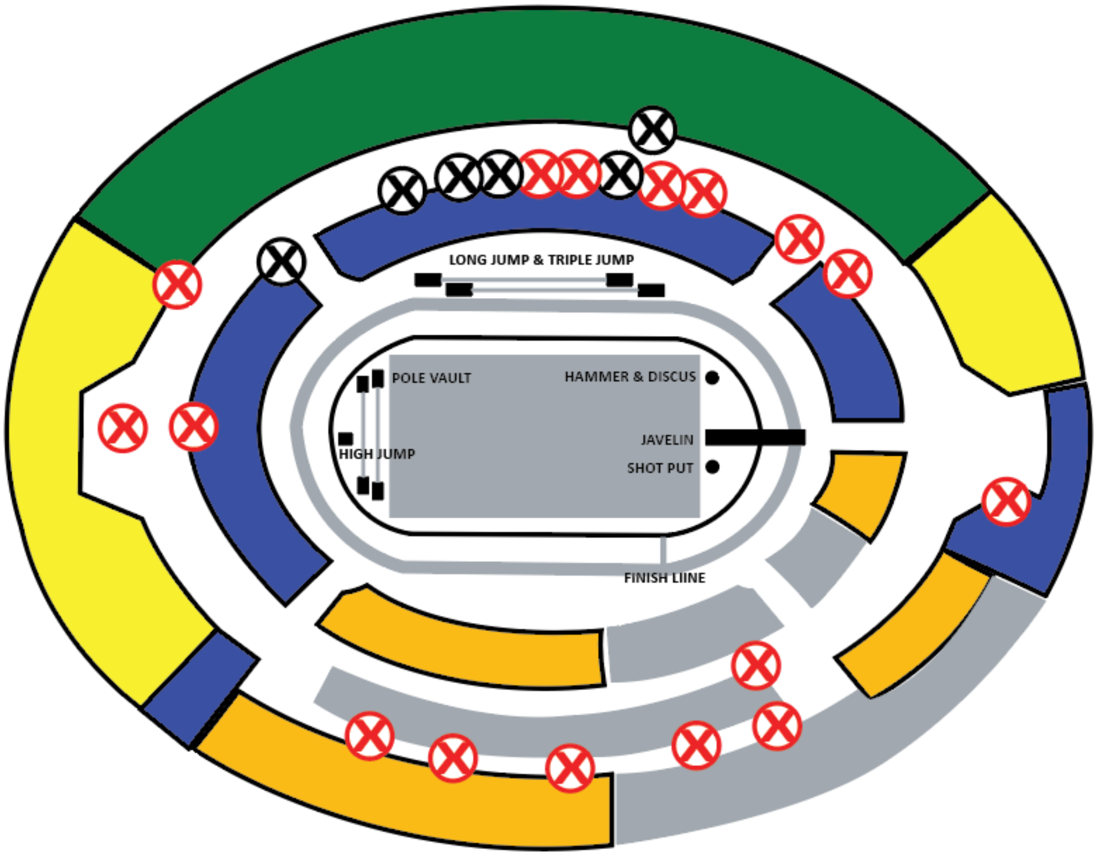


Figure 1.4. WA World Championships London 2017 Men's and Women's Long Jump. Illustrated are the camera layout and locations chosen by black and white-filled circles vs non-selected locations indicated by white and red X-filled circles, from the published 2017 biomechanical reports (*adapted from Tucker, et al., 2018a; Tucker, et al., 2018b*).

These technological and methodological advances progressed Athletic assessments for scientists to acquire more precise data and reevaluate how their work communicated to readers. With the use of high-end equipment and progressive biomechanical measuring techniques during the 2017 WC, reports bundled historical, biomechanical, and coaching analyses for readers of different backgrounds and experiences to consider in their respective sport roles. The context of meet results was supported by analyses of phases in each discipline, time analyses, temporal, and kinematic data. Some key notes and findings from the 2017 WC in two signature track (100-m discipline) and field (long jump discipline) were:

- Women's 100-m Final: the comparison of race position with cumulative split times; calculation of mean and speed and step length per split time was made; duration of acceleration was associated with higher maximum velocity; in accordance to past WC final results, maximum velocity was again the strongest parameter associated to 100-m results; step rate appeared to not be a decisive factor in the high-velocity running phase; and observation in step parameters (step length, step rate) can serve as a method for individualized training (Bissas et al., 2018b).
- Men's 100-m Final: final race conditions included finalists running into a negative wind, analysis was not representative of best performance times achieved by finalists; comparison of race position with cumulative split times; calculation of mean and speed and step length per split time was made; inconclusive left-right differences were due to limb asymmetry but a result of an increase in high velocity; winner displayed the smoothest race distribution and best speed maintenance from mid-way till the end of the race reflecting the trademark of the best sprinters; a mean knee angle at toe-off of 154.0° is a useful marker for coaches to use in assessing technique and sprinting under fatigue (Bissas et al., 2018a).

- Women's Long Jump: distance comparisons before championships; step characteristics of best jump in approach phase; center of mass velocity components (horizontal, vertical, resultant) at take-off; longest best jumps were associated with large horizontal velocity towards end of approach; and transition from approach to take-off with high accurate foot placement is critical to a successful jump (Tucker et al., 2018b).
- Men's Long jump: distance comparisons before championships; step characteristics of best jump in approach phase; horizontal velocities of last three steps; center of mass velocity components (horizontal, vertical, resultant) at take-off; step length between third-last and second-last step increased by 6% for most athletes; step length for last-step had a reduction by 9% for most athletes; high velocities in approach run aid in the preparation for take-off; and transition from approach to take-off with high accurate foot placement is critical to a successful jump (Tucker et al., 2018a).

This project marked an effort towards biomechanical research at the WC in a 7-year span. The project delivered a needed update on the sprint technique of the world's best athletes; provided objective markers to scale an athlete's strengths and weaknesses; and offered progress for athletes over time during qualifying sprint and jump rounds (Bissas et al., 2018a; Bissas et al., 2018b; Tucker et al., 2018a; Tucker et al., 2018b). This suggests these deliverables have spurred global interest in the sport by members of the Athletic community and sport science field. World Athletics President Sebastian Coe dually notes the growth in project reports through modernized technology, the importance of biomechanics in athlete development, and the relationship between the two. Offered by Coe, "…*the reports over the three decades show how far technology and technics have come over these 30 years and give a rare insight into the evolution of biomechanical data in our sport over this time…*" and concludes by adding, "…*biomechanics are crucial to the development of athletes where milli-seconds and millimetres can make the difference between qualifying for a final, or not, and winning a medal, or not. They enable athletes and coaches to perfect performances, tweak technique, and more importantly, understand, manage, and mitigate injury…*" (World Athletics, 2018). The reports highlighted key measures and factors related to informing where performance is currently at the most desired peak time and where performance could change based on considerations formulated. This gives credence to future projects yielding reports on major and championship meets.

A well-known and respected championship-caliber meet is the National Collegiate Athletic Association (NCAA) Outdoor Track & Field Championships. The World Championships (WC), held on a biennial cycle, were postponed by WA in 2021 due to the COVID pandemic. The featured major championships of the year became the NCAA Track & Field Championships. The history of these championships has produced world-class performance times and marks by some of the best collegiate athletes since its inception. Despite its great history, to the author's knowledge, no project, similar in magnitude or complexity to the 2017 WC, oversaw a biomechanical collection of the NCAA Track & Field Championships, has ever been completed in the U.S. This collection captured kinematic data, motions of the body without regard to forces, to evaluate the possible decisive factors of performance in qualifying and final rounds.

Among the many factors studied in sprint and jump disciplines include acceleration, velocity, and asymmetry. The ability to accelerate, in Athletics or sports in general, has markedly been known to influence performance (Brüggemann & Sušanka, 1990, Mero et al., 1992; Brüggemann et al., 1999, Majumbar & Robergs, 2011; Maćkała et al., 2015; Bissas et al., 2018, Bezodis et al., 2019; Valamatos et al., 2022; Wild et al., 2022). Literature reveals in major championship meets men are in the acceleration phase longer than women in the 100-m (Brüggemann & Sušanka, 1990; Brüggemann et al., 1999; Bissas et al., 2018; Bissas et al., 2018), while production of speed (horizontal velocity) is a necessity for acceleration in the approach of the long jump (Brüggemann & Sušanka, 1990; Brüggemann et al., 1999; Tucker et al., 2018; Tucker et al., 2018). Whether in a race or on the runway, an acceleration phase must produce maximal forces to push the body in a forward direction (Brüggemann et al., 1999). Achieving an efficient acceleration builds upon the next phase in Athletic disciplines.

Following the acceleration phase, sprinters and jumpers rely on a transfer of velocity to reach the minimum requirements needed to sustain speeds (100-m) and take-off accuracy (long jump), respectively. London WC Men's 100-m analysis reported the difficulty of some finalists transitioning from acceleration to maximal velocity, thus affecting final race positions (Bissas et al., 2018). The transition from approach to take-off in the long jump was reported to be one of the most important elements of the long jump technique (Tucker et al., 2018). Once the transition is attempted, reaching high speeds that are maintained in the 100-m and minimal loss in velocity at the take-off in the long jump are both critical components to championship performance times and marks

(Brüggemann & Sušanka, 1990; Brüggemann et al., 1999; Bissas et al., 2018a; Bissas et al., 2018b; Tucker et al., 2018a; Tucker et al., 2018b).

A common trend carried through over 30 years of biomechanical reports is identifying where the high-velocity running phase occurred for sprinters. Along with presenting data on step rate and step length, correspondence between speeds reached and times posted was recognized. The highest measured speeds in past WC included the following: Rome 1987 – women [10.87 m/s], men [11.76 m/s]; Athens 1997 – women [10.68 m/s], men [11.80 m/s]; London 2017 – women [10.66 m/s], men [11.84 m/s] (Brüggemann & Sušanka, 1990; Brüggemann et al., 1999; Bissas et al., 2018a; Bissas et al., 2018b). Data suggested from these championships revealed maximum velocity to be a precondition of excellent performance, crucial for succeeding in sprinting, and has the strongest relationship with final race results (Brüggemann & Sušanka, 1990; Brüggemann et al., 1999; Bissas et al., 2018a; Bissas et al., 2018b).

Studies of acceleration and maximum velocity may communicate asymmetrical differences during foot contacts made in those phases. Running is said to be a continuous task dependent on coordinated movement of both lower extremities (Zifchock et al., 2008a; Wayner et al., 2023). Researchers have shown the magnitude of asymmetry varies across variables of interest and asymmetry values were slightly higher in kinematic variables (Wayner et al., 2023). Kinematic variables associated with asymmetry in championship setting include but are not limited to ground contact time during sprint and jump phases. London WC reports indicated asymmetry being present for some male finalists based on longer contact time of one limb over the opposite (Bissas et al., 2018a).

Evaluating asymmetry in connection with ground contact time during select sprint and jump phases has value.

Additional research is needed to reveal any left-right differences during the acceleration and maximum velocity phases in select Athletic disciplines. Efforts towards the combination of acceleration, maximum velocity, and asymmetry dynamics have the potential to provide implications for coaches to address the variation in technical skills in short sprint and horizontal jump disciplines needed in and out-of-competition environments.

Three decades of biomechanical reports on major world championships have yielded a wealth of knowledge on steps Athletics has taken in its development. Reports have highlighted factors found most closely associated with sprint and jump phases. This includes, but is not limited to, changes in stride rhythm during phases, transition preparation into proceeding phases, and characteristics of touchdown and take-off positions. Project results identified the factors which determined the techniques used and the caliber of athlete performing at the world level.

However, there is a need for further research to assess who has been considered the sub-elite (college) level likely to feed the elite division: what techniques are being employed and how performance trends are being established. Casting a biomechanical analysis on a wider range of athletes presents a greater opportunity for the coaching and scientific field to enrich their understanding of sprint and jump mechanisms. Ultimately, the knowledge of what caliber of athlete exists at the college, as it’s known on the elite level, moves forward the sport of Athletics. The need for more information can be expressed as the following:

- What mechanisms in sprinting and jumping underscore high-caliber collegiate performance?
- What accelerative and velocity techniques in sprint and jump performances explain the mechanisms expressed in collegiate competition?
- Do kinematic performance values in collegiate Athletics show new trends in sprinting and jumping?

Thus, the present project aspires to effectively define and communicate how sports science can be deduced and applied by coaches to instruct collegiate athletes in their respective disciplines leading up to and for major championships. The NCAA Championships will be this project's feature event in which a focus on kinematic parameters related to acceleration, velocity, and asymmetry in the 100-m and long jump will be examined.

It is intended to inform on the movements achieved during performance in the competitive arena in which coaches look to instruct and prepare athletes based on their projected potential. Providing an unprecedented view in this manner looks to empower coaches through a scientific lens while adding to existing sports literature. This project represents an addition needed to the collegiate marketplace of sports performance in the U.S.

Therefore, the aims of the present project will: a) support coaches and athletes in constructing high-caliber collegiate performances, with the potential of being world-class, at championship competitions, b) set the standard for reports being produced on collegiate championship meets for future comparative studies in the competition environment versus a training or testing environment, and c) investigate the kinematic mechanisms and techniques used in competition, where it counts most, to better understand how athletes can take practice work to the competition arena.

Chapter 2

REVIEW OF LITERATURE

2.1 INTRODUCTION

This chapter provides a literature review on the nature of this project with a focus on coaching and scientific perspectives. The review critically investigates the kinematics of the signature disciplines in Athletics: 100-m and long jump. The focus of this review leads with the coaching and scientific perspectives in Athletics into the biomechanics of sprinting (acceleration, maximal velocity) and the biomechanics of the horizontal jumps (development of acceleration into horizontal velocity). The presence of asymmetry and its potential effect on sprint and jump disciplines have been weighed upon as well.

2.2 COACHING PERSPECTIVE

Sport coaches can be considered the first teachers, and first instructors of movement and training in organized sports. Athletic (*Track & Field*) coaches serve in this capacity, employing practical knowledge and their understanding of movement in a given discipline and environment. The directives of an Athletics sprint and jump coach are aimed at supporting the athlete to achieve success, based on what the demands of sprinting and jumping require at the highest competition level available. The demands of each discipline have challenged but also kept coaches engaged, yielding trends of faster times and farther jumps. Thus, coaches are intent on improving athletic performance while minimizing the chance of injury in their efforts.

To meet their intent, coaches have been reliant on their intuition, experience, and tradition in the training and coaching of elite athletes to a greater extent than research-based evidence (Haugen, 2021). They learn from mentors and fellow coaches in their attempt to guide their athletes. Some have drawn from scientific fields—biomechanics, physiology, psychology—to determine whether their approach to competition preparation is optimal for desired improvements. The field of biomechanics has become invaluable to the development of athletes and a supportive tool for coaches to apply in Athletics.

Rather than coaches having a low level of biomechanics knowledge, researchers have found coaches have been simply interested in different areas of biomechanics and possess differing goals and knowledge compared to biomechanists (Waters, et al., 2019). Coaches defer to what is recognizable and commit to what has been most successful for them while being strategic in what new measures of preparation are implemented. The importance of understanding the application of science to answer the question “why” a technique or execution of a skill should be done a certain way, has been given recognition by some coaches (Norman, 1975; Thompson et al., 2009; Waters et al., 2019). A coach's philosophy considers the "why" with a combination of their coaching skill, intuition, and leverage of an athlete's idiosyncrasies (Ozolin, 1986; Haugen, 2021). The goal becomes for any implementation to necessitate an athlete's ability to reach projected performance marks needed at the most opportune times of the season. Preparation goals should be constructed around effective ways to tailor toward athlete profiles.

To prepare for competition, coaches look to structure training based on what can affect but also direct performance outcomes needed at major championship levels. It is assumed that affected concepts are based and governed by three physiological principles: 1) overload - increase in training loads sufficient to cause an improvement; 2) specificity - training load that is specific towards the desired effect); and 3) reversibility - training effect reverting based on a decrease in training load (Volkov, 1974; Freeman, 2001). Directing performance outcomes are based on iterative processes such as: 1) the scope and depth of improvement; 2) monitoring of training stimuli and testing outcomes; (Stone & Gray, 2010); 3) continued reevaluation of practices; and 4) making informed decisions in fast-moving environments (Coutts, 2016; Coutts, 2017). Within these principles and processes, a systematic approach towards training is taken to develop a blueprint for what high-level competition demands. Biomechanical-driven film analyses of competitions can further attempt to answer or dispel impressions athletes and coaches have of performances observed, thus offering novel insights into how best to direct performance.

Competition prompts coaches to intuitively look for reactions and movements made by athletes. Based on those observations, coaches then aim to give instructions and feedback to address delayed reactions and inefficiencies in movement. A coach must effectively communicate appropriate verbal instructions, cues, and feedback to enhance performance (Benz, et al., 2016). Instructions and cues facilitate: 1) an athlete's attentional focus—"defined by conscious ability of an individual to focus their attention through explicit thoughts in an effort to execute a task"; 2) a meaningful impact on motor performance; and 3) how a coach or sport scientist (e.g., biomechanists, data analysts, lecturers, physiologists) communicates with an athlete (Benz, et al., 2016). It can be inferred that detailed footage review and analysis may aid coaches in choosing the most fitting cues and instructions to improve reactions and movements. The quality of the instruction and cues refers to achieving the intended result (Benz, et al., 2016). Thus, the constant desire for improved results has drawn discussions between coaches in preparation for the next competition.

A coach's impression of observed performances is further rooted in how the effectiveness of a training stimulus' is valued, what an athlete's adaptation to a stimulus' is, and the effect of a stimulus' in competition. It is presumed major competition preparation involves an athlete being conditioned to endure and adapt to the physical demands their discipline imposes on them. Based on the nature of short sprint (100-m) and horizontal jump (long jump) disciplines, the demands of competition rounds and flights can biomechanically affect positions athletes reach during phases. The 2017 London World Championships (WC) biomechanical reports indicated running mechanic differences between finalists who ran all qualifying rounds of the 100-m and 200-m during acceleration and maximum velocity phases, suggesting fatigue is a contributor to these changes (Bissas et al., 2018a; Bissas et al., 2018b; Pollitt, et al., 2018a; Pollitt, et al., 2018b). This suggests a detailed biomechanical analysis of championship meets may provide collegiate coaches and athletes with information about: a) mechanical sprint changes, b) transitional changes between sprint phases, and c) how to manage running through sequential qualifying rounds and flights, all for future performance preparation.

Preparation for future competition should ultimately involve what affects how movement is demonstrated in competition. This is reflected in biomechanical specificity, kinematic and kinetic parameters—acceleration, angles, forces, positions, range of motion, times, and velocities (Gamble, 2013; Slawinski, J. et al., 2010; Amara et al., 2019; Gleadhill & Nagahara, 2021). Each of these metrics can provide insights into quantifying athlete performance while being difficult to interpret at times. Coaches, in turn, need to process these parameters into meaningful decision-making guidelines to improve their athletes' performance. Decision-making by coaches can be defined as a "commitment to a source of action that intended to yield results for specified individuals" where steps are taken by coaches beyond evaluating amongst options (Yates & Tschirhart, 2006; Berry, 2020). Therefore, coaching experience, knowledge, and understanding of biomechanical parameters influence the constant subjective visual evaluation of athletes' performances during training and competition. Some are simply obvious or useless: yes, the 'fastest' or 'most-talented' individual will win the sprint or jump the farthest, but coaches must make training decisions to increase speed or jump distance based on additional biomechanic detail.

To confirm or refute experiences, knowledge, and understandings, the application of biomechanical specificity evaluates performance in two forms, qualitatively and quantitatively. Coaches lead with a qualitative approach when determining the level of adjustment or execution an athlete has made in sprint and jump disciplines. As the science of movement technique, biomechanics serves as the primary foundational contributor to the qualitative diagnoses of human movement for coaches (Knudson, 2021).

Qualitative evaluations satisfy a "systematic observation and introspective judgment of the quality of human movement for the purposes of providing the most appropriate intervention to improve performance" (Knudson & Morrison, 2002). Attempts to achieve desired movements may be described as inadequate, normal, or perhaps excessive in execution (Knudson, 2021). For example, it is reasonable to infer a coach using language such as 'poor knee drive', 'overstriding', or 'reaching for the board'. Biomechanical specificity becomes most beneficial not only when movements are examined but when the cause of those movements is described. When the cause and response of movements are evaluated, an opportunity is available for coaches to give effective instruction on performance inadequacies relative to how an athlete is biomechanically built. For instance, studies have reported anterior pelvic tilt (APT) being closely related to hamstring muscle-tendon tissue injuries faced during sprinting (Danielsson, et al., 2020; Mendiguchia, et al., 2022). While investigating the relationship between pelvic, and lower limb kinematics and performance, researchers showed a multimodal intervention program supports a decrease of APT during the late swing phase of sprinting, potential for hamstring strains, and changes in lower-limb kinematics, all associated with performance improvement (Mendiguchia, et al., 2022). This suggests having sprint kinematic data may provide coaches with information on what to look for related to sprint posture and positions in preparation for competition and limiting injury in the process.

Other studies have shown detailed biomechanical data would be useful to the qualitative process for coaches. Based on spatiotemporal and ground reaction force variables, Gleadhill and Nagahara (2021) elucidated 100-m performance determinants in acceleration and maximal speed phases for coaches to develop race strategies (Gleadhill & Nagahara, 2021). Seidl et al. (2021) demonstrated employing sensor-based detection allowed for a comprehensive sprint diagnostic of kinematic parameters related to acceleration and maximum velocity for competition and training settings. A study on male elite sprinters aimed at investigating kinematic factors associated with successful performance in the initial acceleration phase identified two key joint kinematic variables (trunk lean and thigh separation) (Walker et al., 2021). Walker et al. (2021) were successful in providing coaches with a visual guide to improving technical characteristics of initial acceleration needed in competition. Studies done on learning visualization of different gait (e.g., running) phases or observational gait analysis have shown to increase in the use of gait assessment in wider populations (e.g., number of college Athletic participants vs the number of elite Athletic participants) (Viehweger, et al., 2010). Hence, coaches can extrapolate several measured parameters from biomechanical data to direct athletes in improving the mechanisms responsible for high-level sprinting and jumping.

The mechanism in which sprint and jump mechanics are performed has been debated and shared amongst coaches to determine what is most ideal. Although principles and accuracy are based on Newton’s law of motion, their application of them in coaching has become complex in some instances.

An understanding of Newton’s law has been seen as counterintuitive where principles applicable to rigid bodies are being applied to bodies far from rigid (Dyson, 1962; Knudson, 2007). Coaches knowledgeable about how the body creates and responds in performance have a greater chance of communicating how to incorporate the principles of biomechanics in sprint and jump movements. Denoting motion, all forces should be directly applied in line with the intended motion (Robison, et al., 1974), but should a force not pass through the center of mass (CM), the point will change the body's speed in a direction parallel to the direction of that force (Dyson, 1962). This is seen by a sprinter’s ability to apply force in a more horizontal direction where the same magnitude and horizontal change in velocity, will differ based on the orientation of resultant forces (Bezodis, et al., 2021) or generate higher accelerations with forward-oriented forces (Kugler & Janshen, 2010). It can be inferred that forces contribute to changes in motion, but also how motions are shaped and transformed by forces.

Motions of the body which employ effective techniques are beneficial in creating movements required in sprinting and jumping. Not only does the amount of force increase a body’s motion, but the amount of time over which force is applied affects the resulting motion (Knudson, 2021). This is emulated by the laws of inertia, acceleration or momentum, and reaction. In particular, the body transfers and builds momentum, a measured quantity of motion (mass multiplied by velocity), until it peaks and is maintained for as long as possible (Dyson, 1962; Robison, et al., 1974; Tellez, 2014). A change in momentum is predicated on impulse (force multiplied by time) as a force acting over time (Tellez, 2014; Knudson, 2021). An increase in the body’s motion can occur with a greater application of impulse, notating both the size and duration of the force (Knudson, 2021). At the start of a sprint acceleration, the velocity is zero with the impulse being a combination of force applied over longer ground contacts (Hicks, 2020). As velocity increases, the time in which force can be applied decreases, making quality force application at ground contact essential (Hicks, 2020). Researchers have shown the rate at which acceleration is achieved and its relationship between impulse and momentum: for example, elite sprinters produced greater net horizontal impulse compared to sub-elite sprinters; and elite sprinters maintain their impulse across the duration of sprint acceleration as velocity increases and ground contact decreases (Morin et al., 2015; Hicks et al., 2020; Knudson, 2021). Hence, research implies the importance of fundamental knowledge of biomechanical principles to inform and develop preparation techniques needed for competition.

Efforts to introduce coaches to biomechanics have been incorporated into coaching education programs. Developed by individual Athletic governing bodies intended to educate coaches on sport technique and science-based subfields such as biomechanics (Norman, 1975). In 1975, The Sport and Recreation Bureau of the Ministry of Community and Social Services of the Ontario Provincial Government developed a 3-tier program. Level I served as an introduction to biomechanics and its usefulness in applied coaching techniques; Level II covered qualitative analysis; and Level III focused on quantification motion analysis (Norman, 1975). Today in the United States, USA Track & Field Association (USATF) offers a 3-level coaching certification program along with specialty program education. Similarly, Level 1 introduces all disciplines and basic sports science; Level 2 provides an advanced look into sports science (biomechanics, physiology), technical aspects, and comprehensive training plans for

Athletic disciplines; Level 3 is a combination of a scientific-base and comprehensive knowledge of a specific discipline group (USATF, 2023). Comparably, the England Athletics education program supports the Coaching Journey with qualification, development opportunities, and coaching webinars (England Athletics, 2023). The Coaching Journey offers coaches courses to earn qualifications at an entry-level, coach-level, and event-group level. Based on the level, England Athletics provides development opportunities through talented athlete and coach pathway programs, international Athletics conferences, discipline development, regional coach and athlete training days, and coaching webinars (England Athletics, 2023). Lastly, as the global federation in the sport, World Athletics (WA) operates the Coaches Education and Certification System (CECS) available to member federations (World Athletics, 2023). The three-level CECS structure focuses first on youth under age 16 (Level I – U16 Coach) addressing the development of beginners, practical skills, and theoretical bases for continued learning; the second level focuses on coaching specialization for athletes under age 20 (Level II – U20 Coach), identifying competition models, optimizing the application of course material in an annual training plan, and introducing initial specialization development; and the third level focuses on athletes age 20 and up (Level III – 20+ Coach) developing advanced coaches, implementing meso and macrocycles within the context of multi-year training plans, and leading the achievement of potential elite and competitive results (World Athletics, 2023). Through various avenues, it is assumed the sharing of sports science terminology and general principles of biomechanics has become more ubiquitous among coaches.

The coaching lexicon used to describe important biomechanical concepts includes, but not limited to, acceleration, center of mass (CM), force, power, and velocity. Coaches deduce athletic observations and evaluations using biomechanical terminology based on coaching lexicons (Norman, 1975). Inevitably, coaches go on to determine how to develop technically sound athletes within training specificities. Coaches desire comparative effectiveness studies that offer effective ways to achieve the metrics associated with success in sprinting and jumping.

Although terminology usage may not be uniform among all Athletic coaches, coaching lexicons are construed within and based on a coach's philosophy and experience. Coaching instruction is intended to be delivered in a basic form despite the complexity of some terms when scientifically integrated. Of the many terms used in biomechanical specificity during athlete-coach or coach-coach interactions, acceleration, maximum velocity, and asymmetry have become commonplace terms. Terminology descriptions have varied but still embody biomechanical principles.

Keeping in mind the scientific definitions, Jacoby defines acceleration from the coaching view as the mean time for a runner to go from a standstill to maximum speed, while maximum velocity is defined as top speed held under the ability to run relaxed (Jacoby, 1983). Based on coaching descriptions of acceleration and maximal velocity, the relationship between these determinants has been further explored and shown to play a major role in the initiation and transition of movements in Athletics. Sprinters who lost velocity were given the term negative acceleration, whereas if a sprinter was able to pick up speed, positive acceleration was the term used (Dyson, 1962). The combination of a complete acceleration and maximal velocity phase has been shown to directly be related to performance (Mero, 1988; Mero et al., 1992; Delecluse et al., 1995; Delecluse, 1997; Morin et al., 2015).

With acceleration and maximal velocity as the foundational phases in sprinting, the association of symmetry and performance has been recognized by coaches. From a coaching view, symmetry is the observed differences in gait mechanics and strength (Zifchock, 2018; Iwańska et al., 2021). Dynamic lower limb strength asymmetry was established in years past as a key determinant in sprint positions (Vagenas & Hoshizaki, 1986). Trivers et al. (2014) postulated a positive association between lower body symmetry and sprint speed based on symmetry being efficient and less physically demanding. Research findings by Maćkała et al. (2010) indicated unique asymmetry existed within stride length during out-of-competition 200-m sprints among novice, intermediate, and advanced national and regional level sprinters (Maćkała et al., 2010). A more recent study on sprint stride parameters of sprinters competing in the 100-m Athletics WC found asymmetry to be inconsistent in the mechanics of maximal velocity (Bissas et al., 2022). Based on these terms—acceleration, maximal velocity, asymmetry—coaches use their experience to instruct athletes accordingly.

Coaches have acknowledged and formed their understanding of acceleration, maximal velocity, and asymmetry as determinants of performance. Coaches have the challenge of understanding what role these determinants play in competition versus training sessions and how to manage the expression of these determinants within environments where the best performances are needed.

2.3 SCIENTIST PERSPECTIVE

The sports science view proposes to discover connections between sports movement and science through biomechanics. Biomechanics is seen as a focus on the mechanisms through which the components of musculoskeletal anatomy interact to create movement (Baechle & Roger, 2008). Past research considered biomechanics as "the study of human motion by combining certain principles of physics (in particular, mechanics) with knowledge of the physiological and anatomical characteristics of the person to determine how a particular movement should be performed" (Norman, 1975). Today, scholars have viewed the study of biomechanics as a conceptual and mathematical tool necessary for understanding how living things move and create forces in movement (Knudson, 2021).

Biomechanists engage in investigations that may answer questions raised about measures used to improve and/or limit flaws when performing movements. Hence, the application of biomechanics in sports is of great interest to many biomechanists striving to explain specific, real-world movement problems (Knudson, 2021). Scientific problem-solving has been led with critical reviews of evidence with contextual and practical considerations interested in science translation for sports performance (Faulkner et al., 2006; Slattery et al., 2021). Trained biomechanists learn the process of study design, methodology, and practices from previous studies led by researchers in specific areas of interest. Studies are often conducted in lab-controlled settings where the operation of advanced equipment is needed for data collections. From sports equipment (running spikes, running shoes, throwing implements) to muscle actions (concentric, eccentric, isometric), to sports movements (running, throwing, lifting), lab environments have been custom-built to collect the most accurate biomechanical values possible. Lab environments are based in slower-operating research settings where large data sets with robust statistical analyses are completed, reported, and translated (Coutts, 2016; Knudson, 2021). Although there have been several sports biomechanics research projects, scientists have reported no reduction in cost for good biomechanical research with advanced computer and software programs (Knudson, 2007).

Funding and grants have monetarily supported the biomechanical field targeting injury prevention and treatment over applied sports biomechanics as seen in countries where government funding is focused on treating disease (Knudson, 2021). Dating back to the 1987 Rome World Athletic Championships, the IAAF recognized, top-level research was beyond the financial capabilities of most countries, thus a need to distribute project scientific information for the development of Athletics (Brüggemann & Sušanka, 1990). Subsequent projects and reports continued to be shared in other world championships by the IAAF. Despite the global efforts on the part of the IAAF, the U.S. has organizations such as National Institutes of Health (NIH) and American College of Sports Medicine (ACSM) committed to their mission of engaging in research that enhances health, reduces illness and disability; and advances physical activity epidemiology and clinical sports medicine (NIH, 2023; ACSM, 2023), respectively. With funding limitations, the landscape of training and competition environments has challenged scientists to keep pace with the innovation and renditions of equipment, techniques, and training used by athletes and coaches. Scientists still have the task of formulating meaningful biomechanical research questions, defining variables, and interpreting data irrespective of “high-tech” equipment or software (Knudson, 2007; Lees, 1999).

The development of evidence-based practices should reflect where innovation in high-performance informs on decisions made in athlete preparation (Coutts, 2016; Coutts, 2017). Continued integration between experimental lab and empirical knowledge may encourage the uptake of innovative and novel approaches to athlete learning (Renshaw, 2019; Stone, 2020) in competition. Although research practices and evaluations may offer insights into the coaching field, there is value in understanding the quantitative scientific approach.

Biomechanical principles have led biomechanists to direct sport evaluations quantitatively. From the scientific view, quantitative evaluation involves measuring variables of interest and subsequent calculations using those numerical values (Knudson, 2021). The quantitative process grants the most accurate, consistent, and precise data collected using calibrated, computational, and processing methods (Knudson, 2021). An important aspect of quantitative measurements in sports medicine and science include: a) reliability implying better precision of single measurements and tracking of changes in measurements in research or practical settings, and b) validity, referring to evidence between the observed value and true or criterion value of measure (Kerlinger, 1986; Hopkins, 2000; Cohen & Swerdlik, 2005; Cranmer et al., 2017). Scientists use statistical guidelines and statements to assist in their analysis and reporting of sports science, thus enriching quantitative projects that make greater use of qualitative methods (Hopkins et al., 2009) used by coaches in preparation for competition settings.

While athletes and coaches navigate through uncontrolled environments, scientists attempt to construct studies in controlled lab settings that have set valid, reliable, and repeatable standards of sports research. Scholars state a compromise of the accuracy and reliability of scientific principles should not be, but the importance in applied circumstances to evade masking the effect of an experiment, with clinical studies having contributed to the rise in reliability studies of dynamic movements involving human movement (Salo et al., 1997). It can be inferred that biomechanists have further exercised the concepts and laws which distinguish biomechanical principles and specificity related to sports such as Athletic disciplines.

Biomechanists have used Newton's laws of motion as the foundation for what creates motion. The laws determine the motion of biomechanical systems and objects (Robertson & Fleming, 1987; Knudson, 2021). Known to biomechanists as the Law of Inertia, Newton's first law stated a body at rest tends to remain at rest whereas a body in motion continues in motion with consistent speed and in the same direction unless acted upon by force (Robison et al., 1974; Knudson, 2021). Newton's second law, Law of Acceleration or Momentum, written as mass multiplied by acceleration to equal force ($F = ma$), demonstrated to scientists the fundamental mechanical relationship on the causes of performance (Winter et al., 2015). Biomechanists translated the third law of motion, Law of Reaction, to be for every action, there is an equal and opposite reaction (Knudson, 2021). These laws directed how motion was analyzed and calculated mathematically. To further communicate research findings, scientists have used scientific terminology to describe sports movements.

From experimental variables to muddled scholarship writing, terms used to explain the phenomenon behind the mechanisms of sequential coordination observed in movements have affected the application of biomechanics (Knudson, 2007). Despite these differences, similar to the coaching view, scientists have defined acceleration, maximal velocity, and asymmetry. Scientists have viewed acceleration as an important motor skill dependent on the athlete's capacity to produce a net horizontal force on the ground aimed at covering distance in the shortest time possible (Morin et al., 2012; Rabita et al., 2015; Colyer et al., 2018; Samozino et al., 2021; Wild et al., 2022). Thus, acceleration is defined as an unbalanced force in a particular direction due to the rate of change in velocity (Knudson, 2021). Often mistaken for speed (*rate of change of distance in how fast an object moves without regard to direction*), scientists have defined maximal velocity as the rate of change in displacement as a vector quantity corresponding to speed at a maximum point (Knudson, 2021), characterized by a gradual increase in velocity and highly correlated with performance success (Seagrave et al., 2009; Healy et al., 2022). Seen as functional between limbs, scientists have referred to asymmetry as the difference in the performance of one limb in relation to the other (Maćkała, 2021). Scientific fields continue to be drawn to these determinants as independent variables, in connection with each other, and their contribution to sprint and jump techniques in Athletic major competitions.

2.4 PERSPECTIVE SUMMARY

Some would propose history shows the very best coaches often are years ahead of sports science employing critical features of training principles or methods (specificity, recovery strategies, tapering, technical training, etc.) (Haugen, 2019; Haugen, 2021). Others would argue coaches continue to rely on experiential, as opposed to extrinsically presented knowledge, showing a gap exists between coaching knowledge and academic studies (Thompson et al., 2009) of Athletic disciplines.

Revisiting the reasons the former IAAF, now World Athletics (WA), undertook the first biomechanical analysis on the II World Athletic Championships, a commitment to support the development of Athletics in all aspects was made (Brüggemann & Sušanka, 1990) and led to an agreement between the scientific and coaching communities about what constitutes applying biomechanical concepts or principles (Knudson, 2007).

Written from the practical experience and intuition of world-leading sprint coaches and governing bodies of Athletics federations, books, and training guides publicly available to the Athletics community have become important popular sources of best training practices and framework development for the sprint's world (Haugen, 2019; Lee, 2011). The combination of data sources from evidence-based research and results-proven practice provides a valid point and opportunity to outline recommendations and future hypotheses in future research (Haugen et al., 2019) on Athletics championship competition. Therefore, dialogue between coaches and scientists fosters a community that supports informing coaches on athlete performance and what can be considered in training for future preparation.

The nature of training and competition environments is where observation, perception, and instruction are given by coaches during movements made in the moment. The nature of controlled research environments is where collection, calculation, and interpretation of data are made at any time. Both fields express an interest in providing ways in which improvements can be made in performance while limiting injury. Progress in performance-related research will result from the application of a suitable combination of theoretical and experimental approaches (Yeadon & Challis, 1994). The combination of quantification and qualitative analysis should be made for a meaningful application of biomechanics within athletic fields (Lees, 1999; McPherson, 1996). The balance between theoretical and practical conclusions should be targeted toward a transfer of scientific practices into coaching practices for competition.

This project aspires to engage further dialogue on Athletic competition and provide a biomechanical analysis to coaches and athletes looking to move past the next record by giving an unprecedented view into the mechanics of acceleration, velocity, and asymmetry in the highest competition available in U.S. collegiate Athletics, the NCAA Championships.

2.5 BRANCHES OF BIOMECHANICAL ANALYSIS

Based on rigid-body mechanics, the skeletal system is studied as a static or dynamic body (Gamble, 2012; Knudson, 2021). Dynamic motion is described with kinematic and kinetic measures. Kinematic and kinetic measurements relate to the study of motion and the cause of those motions, respectively (Robertson et al., 2014; Knudson, 2021).

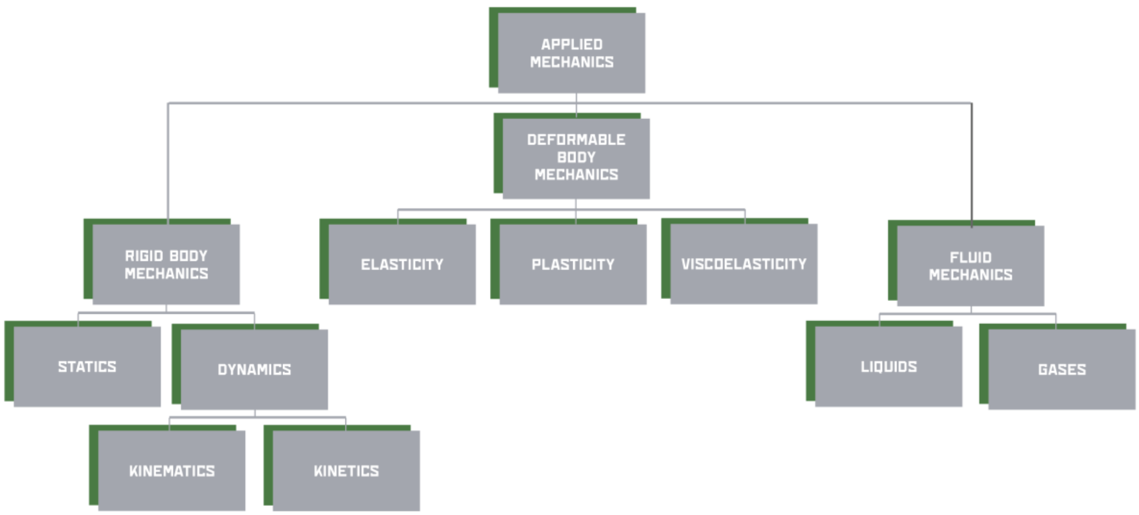


Figure 2.1. Areas of study in applied mechanics (*adapted from Ozkaya et al., 2017; Knudson, 2021*).

Literature shows biomechanical analyses using kinematics and kinetics to study Athletic disciplines. Both branches of biomechanics impart a better understanding and study of the mechanical determinants (Rabita et al., 2015; Jiménez-Reyes et al., 2018; Morin et al., 2019) in Athletic performance. Sprint and jump performances are ultimately determined by the interaction between a number of kinematic and kinetic variables (Bezodis et al., 2008; Morin et al., 2012; Standing & Maulder, 2017). Given the aims of this project, the proceeding review will focus on the kinematic determinants of the sprint (100-m) and jump (long jump) disciplines in collegiate Athletics.

2.5.1 ***BIOMECHANICS OF SPRINT PERFORMANCE***

Sprint performance demands the capacity to perform, and master over time, technical sprint skills where desired expressions of movement in space are made. An athlete's ability to sprint is recognized as the fastest mode of unaided human motion (Mann, 1981). Sprinting is seen as a practical application by coaches and a theoretical application by scientists. The components of sprinting have been investigated through sport biomechanics studies. The sprint disciplines are comprised of three main components: the acceleration phase, the maximal running velocity phase, and the deceleration phase (Majumbar, 2011; Morin, 2011; Wikau, 2018). Components that have been characterized by the velocity-time curve are mathematically represented to explain the theory behind sprinting (Mero et al., 1992, Jiménez-Reyes, 2018). For [someone to sprint or] a sprinter to excel, each component must be mastered individually, then re-assembled to produce a successful race (Seagrave, 1996). Scientific approaches using biomechanics have been used to further understand sprint components individually and in conjunction with each other.

Biomechanics represents the engineering of the body, as a system, and the laws which govern the movement of that system (Tellez, 2007; Knudson, 2021). Certainly, the discipline of biomechanics has contributed to the study of sprint movements. The 100-m sprint has been one of the most featured and studied sprint disciplines in Athletics. There are internal and external mechanics that have been found to aid in sprinting. Internal mechanics relate to levers, moments, and torques created from muscle forces during sprint movements (Judson et al., 2020; Knudson, 2021). Mathematical procedures have been utilized to determine the dominant muscle moments or torques during various aspects of running (Mann, 1983; Morton, 1985; Morin et al., 2011). External mechanics relates to what the body is doing relative to the ground (Mero et al., 1992; Tellez, 2014). During repetitive ground phases, external forces are encountered (Mann & Sprague, 1980). An optimal combination of internal and external mechanics is what efficient sprinting requires (Mero et al., 1992). The expression of these mechanics in sprinting are demonstrated and described through sports biomechanical analyses.

The biomechanical focus on relevant kinematic parameters has contributed to a better understanding of the development of sprint components for coaches and scientists. Kinematic parameters include but are not limited to contact time, step rate, step length, step width, and horizontal velocity. Such parameters are designated as direct performance descriptors used to describe a sprinter's overall performance and continue to be critical in determining the level and nature of sprint efforts (Mann, 1985). To visually distinguish body landmarks and angles related to kinematic parameters, Paradisis and Cooke developed a theoretical model of sprint running (Paradisis & Cooke, 2001).

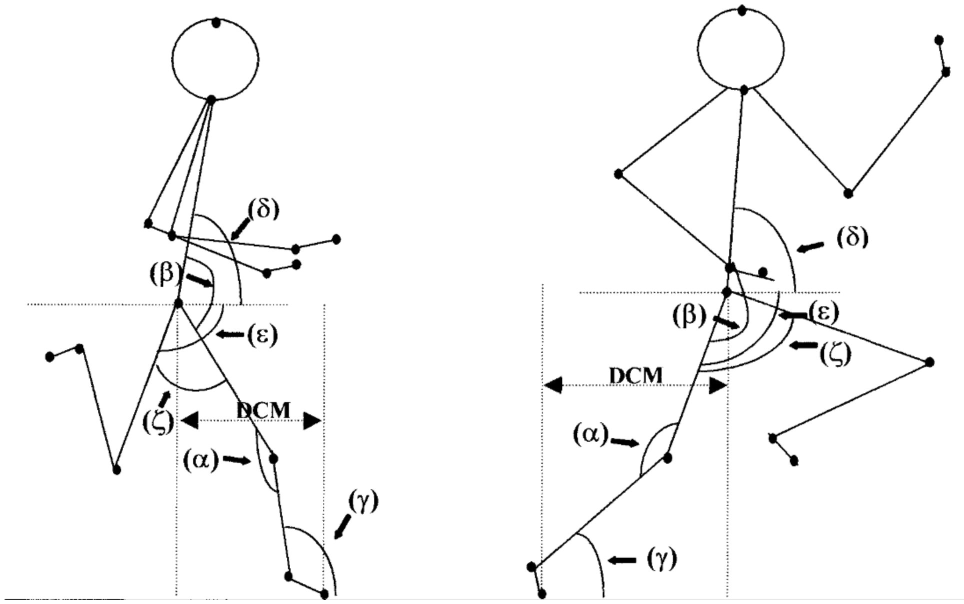


Figure 2.2. Location of the body landmarks and visualization of the angles: knee (α), hip (β), shank (γ), trunk to running surface (δ), thigh to running surface (ε), the angle between the two thighs (ζ) and the distance parallel to the running surface between a line perpendicular to the running surface which passes through the center of mass and the contact point at touchdown and take-off (*reproduced with permission from Paradisis & Cooke, 2001*).

Although sprinting has been extensively analyzed both quantitatively and qualitatively utilizing numerous kinematic variables (Mann, 1983), data collection and data processing in themselves do not constitute sports biomechanics research but govern the extent and form of such research (Yeadon & Challis, 1994). An understanding of sprint performance is dependent on identifying the areas of interest, describing the positions of interest, and examining the mechanics of those areas (Mann, 2015). Objective information about sprint performance is needed when preparing training programs (Delecluse, 1992). It can be inferred training programs serve as the foundation for getting to and performing at a high level in major Athletic competitions.

Coaches have the capacity to assist in improving sprint performance by drawing upon an athlete's current sprint mechanic proficiency while offering insight into how to exploit an athlete's potential. In the Athletic performance environment, this study aims to underscore the nature of sprint mechanics and its indicators through a palpable scientific lens where an application of biomechanical principles is demonstrated within coaching instruction and feedback. Although a concentration of elite athlete projects exists on sprinting, there is limited literature on the mechanics of sprinting of high-caliber sub-elite (collegiate) sprint athletes in competition. For a level, in most cases, that precedes the elite level, an investigation on these athletes in competition may guide coaches in their evaluation of improving performance. Of the short sprint disciplines, 100-m and 200-m, the 100-m sprint will be the focus for the purposes of this project.

2.5.1.1 *Acceleration in Short Sprints*

Acceleration is conventionally defined as the change in velocity over time ($\frac{\Delta V}{t}$) m/s^2. Performing acceleration depends on how an athlete produces, applies, and transmits force in the beginning phases of a sprint. The first steps of sprinting have been thought to control the transformation of joint angular accelerations into an increase of the velocity in the horizontal direction (Jacobs & Schenau, 1992). This suggests forces must be functional where an ability to meet desired sprint technique is not compromised in the development of an acceleration phase.

The acceleration phase is initiated upon completion of the sprint start out of starting blocks. The sprint start is characterized as the period of time between the moment the sound of the starting gun has been received by the participant and the moment both feet have cleared the starting blocks (Majumbar & Robergs; 2011). The completion of a block start is considered purely accelerative, unconstrained in both spatial and temporal dimensions (Majumbar & Robergs; 2011; Eikenberry et al., 2008). Studies have agreed that attaining a high horizontal power during block clearance with an ability to quickly accelerate from the blocks is critical to optimizing sprinting performance (Mirkov, 2020). This suggests mechanical proficiency is needed from a static set position to a dynamic motion in the first step out of the starting blocks to establish acceleration.

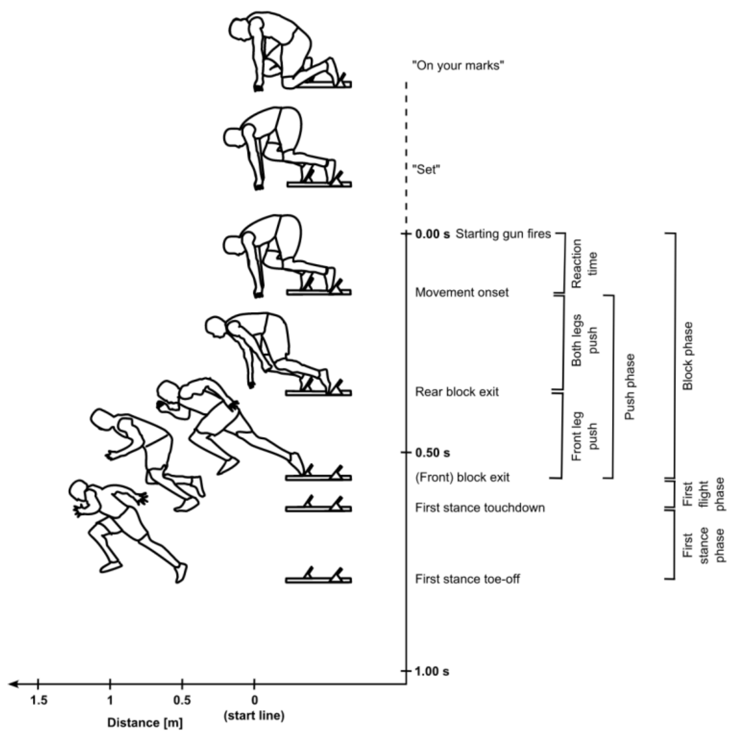


Figure 2.3. A schematic representation and definition of the events and associated phases during the sprint start (*reproduced, without changes, under the Creative Commons license (http://creativecommons.org/licenses/by/4.0/) from Bezodis et al., 2019*).

When evaluating acceleration, it is reasonable to divide it into sub-phases of its own: the initial or starting period being from 0 – 12-m and the main period being 12 – 35-m (Maćkała et al., 2015). Delecluse et al. (1995) confirmed sprint performance to be multidimensional including three components, two of which within acceleration: component 3 – initial acceleration (first 10-m interval) and component 2 – continued acceleration (from 10-m to maximal velocity) (Delecluse et al., 1995). Nagahara et al. (2014a and 2020) supported the notion of sub-phases by detecting three phases (initial [0 to 3 steps], middle [5 to 15 steps], and final [16 plus steps]) and two transitions within the acceleration phase (Nagahara et al., 2014a; Nagahara et al., 2020).

Figure 2.4. Sub-phases and transitions within acceleration phase (*adapted from Delecluse et al., 2017; Nagahara et al., 2014a; Nagahara et al., 2020*).

Kinematically, running speed is the product of step rate (SR) multiplied by step length (SL) (Dyson, 1962; Čoh et al., 2001; Hunter et al., 2004; Maćkała, 2007; Salo et al., 2011; Debaere et al., 2013; Nagahara et al., 2014). Spatiotemporal and kinematic characteristics distinguished each phase: 1) the initial phase, foot contacting the ground behind the body with an increase in SL and SR; 2) the middle phase, foot making contact in front of the body with an increase in SL; and 3) the final phase, having minimal changes in variables along with an increase in speed based on SL (Nagahara et al., 2014a). The two transitions between the phases were distinguishable as the following: a) first transition – foot contacting the ground in front of CG (center of gravity), knee joint flexion during support phase, and termination of an increase in SR, and b) second transition – a slight decrease in hip-joint movement intensity and termination of changes in body postures (Nagahara et al., 2014a). It is important to note the forces applied to the ground are directly responsible for the speed an athlete runs or the increase in speed an athlete achieves. Salo et al. (2011) supported an understanding of SR and SL characteristics in their study of elite athletes in major competitions due to past studies generally identifying only one parameter, SR or SL, as a main reason for faster running velocities. Correlation values between SR and race time (0.16 to -0.79), and SL and race time (-0.16 to -0.89) varied between athletes, demonstrating SR and SL to be inversely linked to race time, strongly related to each other, and reliance on either to be highly individualized (Salo et al., 2011). This suggests there is merit for coaches to consider individual solutions for their athletes to achieve world-class speed based on constant shifts in SR during the acceleration phase with some natural variability appearing later in the sprint and jump phases.

Based on Maćkała et al. (2015) acceleration sub-phases, the relationship between select kinematic determinants has been examined. Nagahara et al. (2014b) demonstrated the importance of having an increase in the SR to the third step, an increase in SL from the 5th to the 15th step, and an increase in SL or SR from the 16th step in the entire acceleration phase, thereby suggesting the acceleration phase can be divided into phases to help coaches identify which phase is weakest to improve sprint effectiveness within the divisions prior to reaching maximal sprinting (Nagahara et al., 2014b). Another study confirmed effective acceleration is likely accompanied by a greater SL to the 8th step during initial acceleration, a higher SR from the 9th to 20th step during the middle and later acceleration phase, and the initial and middle acceleration phase can include up to the 16th step (Murata et al., 2018), suggesting the importance of evaluating acceleration in increments as well as in its entirety. No study to the author's knowledge has examined mechanical determinants of acceleration in a single competitive sprint at the collegiate level.

The movements made during the sub-phases of acceleration are dependent on the combined dynamic behavior of force and center of mass (CM) during sprinting. On one side, the production and application of external forces acting on the body include air or wind resistance, gravitational force, and ground reaction force (GRF) (Samozino et al., 2016). On the other side, the center of mass (CM) or center of gravity (CG) refers to the balance of the body's mass at one point in all directions (Knudson, 2021). CM acceleration is comprised of phases in the horizontal direction. Studies have shown mechanisms in which a sprinter projects their CM to address the task of block and initial acceleration phases (Bezodis, 2019). Researchers reported changes in kinematics (e.g., elevation of CG, trunk angle, foot placement in front of CG) occurring abruptly around the 5th step of the acceleration phase (von Lieres und Wilkau et al., 2018; Nagahara et al., 2014a; Nagahara et al., 2020). An important emphasis for coaches can be made on developing acceleration in phases concerning how force and CM have the propensity to change the state of sprinting. A question remains to what degree kinematic changes have on sprinters in collegiate championship competitions.

An important source of movement and biomechanical factors in sprinting are ground reaction forces (GRFs). It can be inferred that the objective of acceleration is to create movements where a contribution towards forward progress is made with GRFs having an active role in this action.

Figure 2.5. Representation of ground reaction forces (GRFs) (*created by author from live footage taken).*

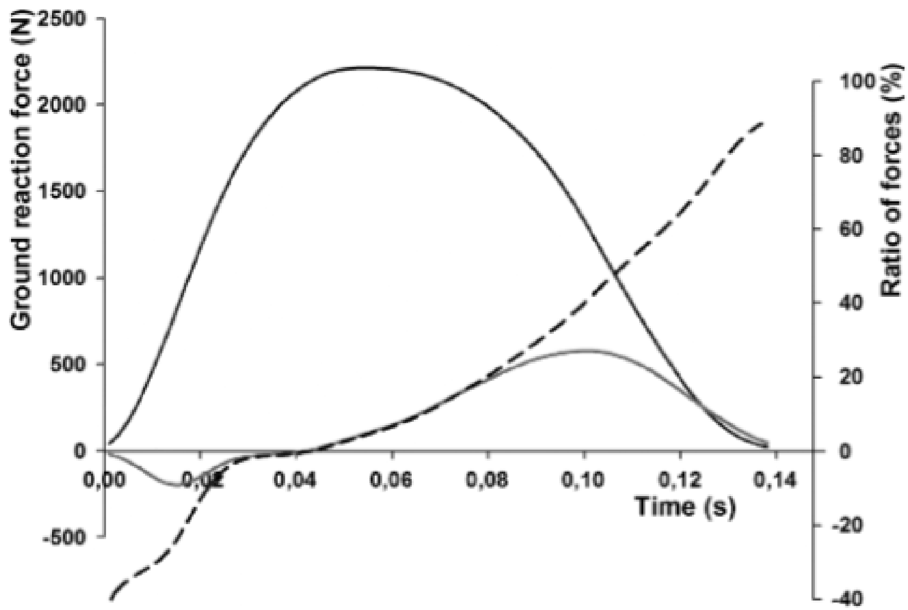


Figure 2.6. Typical traces of vertical (*black line*) and horizontal (*gray line*) GRF and RF (*dotted black line*) during the support phase of a sprint step (*reproduced with permission from Morin et al., 2011*).

During accelerated phase runs, support phases consist of braking phases (negative horizontal GRF) followed by propulsive phases (positive horizontal GRF) (Morin et al., 2011). Previous studies show strong variability in the ratio between the braking and propulsive phase during the first steps taken in acceleration (Cicacci et al., 2010). The braking phase absorbs impact upon foot contact while the propulsive phase generates forward motion (Hunter et al., 2005; Cicacci et al., 2010, Morin et al., 2011). Limiting the percentage of the braking phase is essential to relying on and using optimal SL and SR during the next main phase of sprinting, maximal velocity. This suggests an execution of acceleration requires positions which necessitate technical efficiency for further desired progression to occur in the short sprints.

Horizontal (anterior-posterior) and vertical components have been of typical interest in the case of sprint running based on the hypotheses regarding GRF components (Hunter et al., 2005). Researchers have suggested sprinters should maximize propulsive GRF and minimize the braking of GRF (Mero & Komi, 1986; Mero et al., 1992). Hunter et al. (2005), Yu et al. (2015), and Morin et al. (2015) concluded high magnitudes of propulsion were required to achieve high acceleration. Through a “reconstruction” of a complete 40-m from several sprints taken, Morin et al. (2015) found within the 0-20m acceleration phase, faster sprinters are those able to “push more” (produce a higher amount of propulsive horizontal impulse) and “brake less” (produce a lower amount of braking impulse). It is unknown what propulsive and braking portions of the ground contact phase exist during an acceleration phase in a live major collegiate competition setting.

Along with magnitude, the orientation of GRFs has been quantified as a ratio of forces, RF: antero-posterior (horizontal) component to GRF resultants (Morin et al., 2011; Bezodis et al., 2021). Morin et al. (2015) proposed enacting the mean ratio of forces to sprint running, given a support phase, could represent a sprinters force application technique, independent of the amount of force applied, based on the way force is oriented onto the supporting ground during the acceleration phase of the sprint.

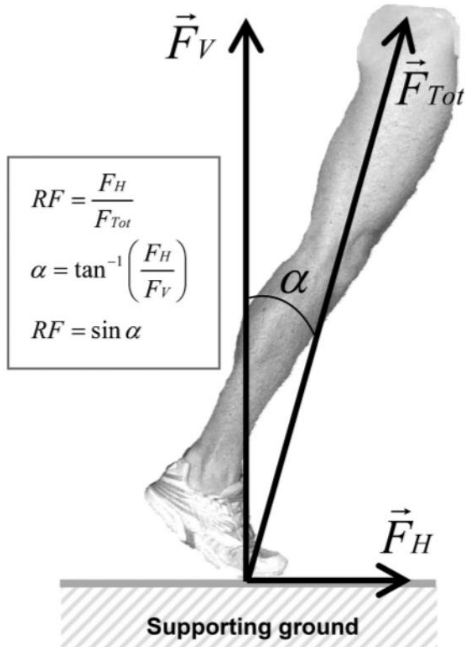


Figure 2.7. Schematic representation of the ratio of forces (RF) and mathematical expression as a function of the total (F_{Tot}) and horizontal (F_H) step averaged GRF. The forward orientation of the total GRF vector is represented by the angle α (*reproduced with permission from Morin et al., 2011*).

Studies on overground sprinting found high RF to be an important key determinant of performance in acceleration (Colyer et al., 2018). A study in a single sprint concluded exerting large propulsive GRFs during an entire acceleration phase is essential to achieving a greater acceleration (Nagahara et al., 2018). RF provides information about the mechanical effectiveness and measurement of a sprinter's ability to apply force in a horizontal direction (Bezodis et al., 2021). Therefore, the orientation of a sprinter is mechanically related to their acceleration (di Prampero et al., 2005; von Lieres und Wilkau et al., 2018). This suggests mechanical progress made through the acceleration phases is a response to not only how an athlete applies, but also transfers forces produced. Kugler and Janshen support this argument by offering higher acceleration is attained by applying forces to the ground at a greater forward lean due to a dominant vertical force component, which in turn will become detrimental to acceleration once greater forces are applied (Kugler & Janshen, 2010).

In the acceleration phase, interesting finds were made in the live biomechanical data collection during the 1987, 1997, and 2017 WC in the times achieved from 0-30-m in the 100-m final based on kinematic parameters. In the 1987 Rome WC, men recorded between 3.80 – 4.33 s while the women recorded between 4.15 – 4.28 s, (Brüggemann & Sušanka, 1990). The 1997 Athens WC captured men recording between 3.67 – 3.76 s and women between 3.94 – 4.08 s (Brüggemann et al., 1999). Lastly, in the 2017 London WC, scientists reported men recording times between 3.77 – 4.01 s and women between 4.18 – 4.25 s (Bissas et al., 2018a; Bissas et al., 2018b). Based on these biomechanical findings, the combination of kinematic and kinetic variables has been measured on sprint performance.

Kinematic and kinetic variables were measured by Kugler and Janshen (2010) to investigate GRFs related to body positions held during accelerated runs. Gleadhill and Nagahara (2021) measured kinematic and kinetic variables in the acceleration and maximal speed phase within a 60-m sprint. Authors found among 15 female WA ranked competitors, a greater SR with a shorter support time (ST) can contribute to later acceleration (also known as transition) sub-phases while an increase in SL and flight time (FT) assists in the running of the initial and middle acceleration sub-phases (Gleadhill & Nagahara, 2021). It was concluded that a combination of spatiotemporal and GRF variables can suggest determinants of sprint performance (Gleadhill & Nagahara, 2021).

Based on studies of this nature, scientists have continued to assess characteristics related to sprint performance.

A recent study by Stavridis et al. (2022) explored the mechanical and kinematic characteristics of sub-elite and recreational sprinters during the acceleration phase using the force-velocity profile method. Scientists determined kinematic (contact time, flight time, SL, and SR) and kinetic/mechanical (horizontal force, velocity, power, ratio of horizontal to resultant force, horizontal force production) characteristics. The study found: a) neuromuscular and technical components affect sprint acceleration; b) sub-elite sprinters benefit from internal mechanisms and functions due to a capacity to attain high sprint velocities and large horizontal forces at those velocities; and c) higher step rates were achieved by sub-elite sprinters (Stavridis et al., 2022).

The above studies suggest the influential factors that affect acceleration and what kinematic and kinetic determinants are associated with those influences. Based on characterizing accelerated running as a continuous change of kinematics (Nagahara et al., 2014a; Ettema, 2016; von Lieres und Wilkau et al., 2018), these changes have yet to be investigated in live major collegiate competition settings.

2.5.1.2 *Transition between Acceleration and Maximal Velocity*

The mechanism in which a sprinter moves from the acceleration phase to maximal velocity begins with a transition phase. From a coaching perspective, transition can be inferred as a process in which an athlete attempts to move through the acceleration period without excessive or abrupt changes in posture leading to premature upright positions seen in later phases (e.g., maximal velocity, deceleration) of the 100-m. From a scientific perspective, the transition phase constitutes an athlete aiming to maximize forward velocity while controlling upward and medio-lateral velocity (Debaere et al., 2013), attributing to contact times being larger, and flight times being shorter (Hoyt et al., 2000; Čoh et al., 2001; Salo et al., 2011). Thus, the transition phase is referred to and characterized as the late acceleration phase in which runners almost reach their top speed values (Brüggemann, et al., 1999). Speed development data has marked the 30-m line as the start of the transition phase (Brüggemann, et al., 1999). Aiming to find morphologic and kinematic characteristics differences between elite sprinters, Čoh states 100-m sprint results depend on the integration of its phases (Čoh et al., 2001), which would include the transition phase between acceleration and maximal velocity.

The transition phase brings about mechanical changes in running position and stride (Seagrave, 1996). Colyer et al. (2018) draw attention to sprinters having lower step-to-step velocity and inevitably reaching a velocity at which they can no longer generate positive net impulse, as acceleration progresses into maximal velocity, as a result of transition. The specific measurable characteristics associated with the transition phase include trunk angle, contact time, and flight time (Čoh et al., 2001; Debaere et al., 2013). One can conclude characteristics contribute to strategies adopted during the transition phase (Debaere et al., 2013) and affect sprint technique carried over in the next phase of the 100-m.

Although the specific length of the early phases of sprinting may differ based on an athlete’s ability to transition from one to another, progressive postural measures have been identified during maximal sprinting (von Lieres und Wilkau et al., 2018). Step-to-step changes in the CM height have also been reported based on measured spatiotemporal and kinematic variables of breakpoint steps (steps 4 to 14) (Nagahara et al., 2014). Further research noted step-to-step sprint progressions to be related to the shank and trunk angles becoming more perpendicular as acceleration ends, alluding to a sprinter having a greater ability to manage touchdown over toe-off mechanics transitioning from initial acceleration to maximal velocity (von Lieres und Wilkau et al., 2018). Hence, it can be inferred that the transition phase directs what positions and postures occur upon ground contact leading into and eventually held during a maximal velocity phase.

Identifying measurable kinematic parameters can support coaches in recognizing and perhaps augmenting transition patterns performed in high competition. To date, biomechanical analyses have captured kinematic parameters in high competition on elite athletes, but not on the best collegiate athletes, who arguably represent world-level or the next group of elite athletes to come. A question remains as to what extent college is similar, different, or perhaps above what has been seen of the elites.

2.5.1.3 *Maximal Velocity in Short Sprints*

Velocity is conventionally defined as displacement over time ($\frac{\Delta X}{t}$) m/s. Maximal running velocity follows acceleration upon a transition period. Kinematically, the body's forward lean decreases where a rise in continuous velocity is made due to increases in SR and SL (Nagahara et al., 2014a; Nagahara et al., 2014b). Depending on the parameter, a quantitative approach may show an overall improvement in velocity may occur due to an increase in that specific parameter. It has been reported top-level sprinters reach their maximum speed between 50-70-m predicated on having sufficient length and optimum running speed during the acceleration phase (Maćkała et al., 2015).

In major championship settings of the 100-m final, elite men and women reached maximal velocity at the 1987 WC between 50 – 70-m and 40 – 60-m, respectively; elite men reached maximal speed at the end of 60-m and women between 40 – 60-m at the 1997 Athens WC (Brüggemann et al., 1999); and at 2017 London WC, men reached maximal speed between 50 – 70m and women between 40 – 60-m (Bissas et al., 2018a; Bissas et al., 2018b). Sprinters attempt to accelerate for as long as possible before going into maximal running velocity. It can be inferred velocity at a maximum level is only hit and held for a limited amount of time. Consequently, sprinting momentum is built until it peaks and an attempt to maintain and decelerate as little as possible is made (Tellez, 2014).

Velocity, as it relates to maximal running, is the product of step rate or frequency (SR (Hz)) and step length (SL (m)). Step rate (SR) is known as the rate at which foot contact is made. Scientists have attributed a sprinter's SR as a determinant of performance to be dependent on genetics, muscle structural characteristics, and running technique (Harland & Steele, 1997; Čoh et al., 2001; Korhonen et al., 2009). Step rate (SR) was recently used to categorize distinctive running styles for future measurement and interpretation (van Oeveren et al., 2021). Step length (SL) is the distance between each foot contact. In contrast to SR, SL has been found to be dependent on body height and leg length which the athlete cannot control (Čoh et al., 2001, Mann, 2015). Scientists have reported: a) SL to be a maximum contributor to running speed between the 50 – 80-m segment of the 100-m (Chatzilazaridis et al., 2012); b) significantly longer at 40-m in the maximal velocity phase compared to the mid-acceleration phase (Yu et al., 2015); and c) influential in the 100-m velocity curve more than SR (Maćkała et al., 2007). It is important to note that these two determinants are not mutually independent of each other, as a decrease in air time can facilitate an increase in SR causing a decrease in SL, whereas an increase in air time can facilitate an increase in SL causing a decrease in SR (Mann, 2015).

In comparing biomechanical variables between world-class sprinters and decathletes running the 100-m at international championship-level meets, Kunz and Kaufmann's data showed an optimal combination of a higher SR and larger SL by world-class sprinters, indicating the contribution of SR and SL differences in the 100-m performance (Kunz & Kaufmann, 1981). Similarly, the efforts of the Elite Athlete Project, directed by Mann, gained an understanding of what made a good sprinter and how to make a good sprinter a great performer by comparing elite and sub-elite sprinters (Mann, 1983; Mann, 1986; Mann & Herman, 1985). Step rate and SL were referred to as "direct performance descriptors" detailing the performance level rather than identifying how the sprint was produced (Mann, 1986; Mann & Herman, 1985). It was concluded elite sprinters' turnover rate was 15% faster than sub-elite (college-level), thus revealing direct differences in performance were related to horizontal velocity and SR in the 100-m sprint (Mann, 1986; Mann & Herman, 1985). It is not known if the percentage and difference hold true today for college sprinters. At present, Mann states research in sprinting unequivocally indicates improvement in SR and is the means by which the better sprinter improves performance (Mann, 2015).

To investigate the interaction of SR and SL as key kinematic parameters, a deterministic model was developed by Hay, displaying a hierarchical structure designed to: 1) explore the interactions of different parameters and their relative influence (Hay, 1993a), and 2) express performance results by a few factors further divided into more factors versus making a correlation of all available parameters (Yeadon & Challis, 1994). The deterministic model provided a road map of the parameters within maximal running velocity as key factors contributing to high-level sprinting.

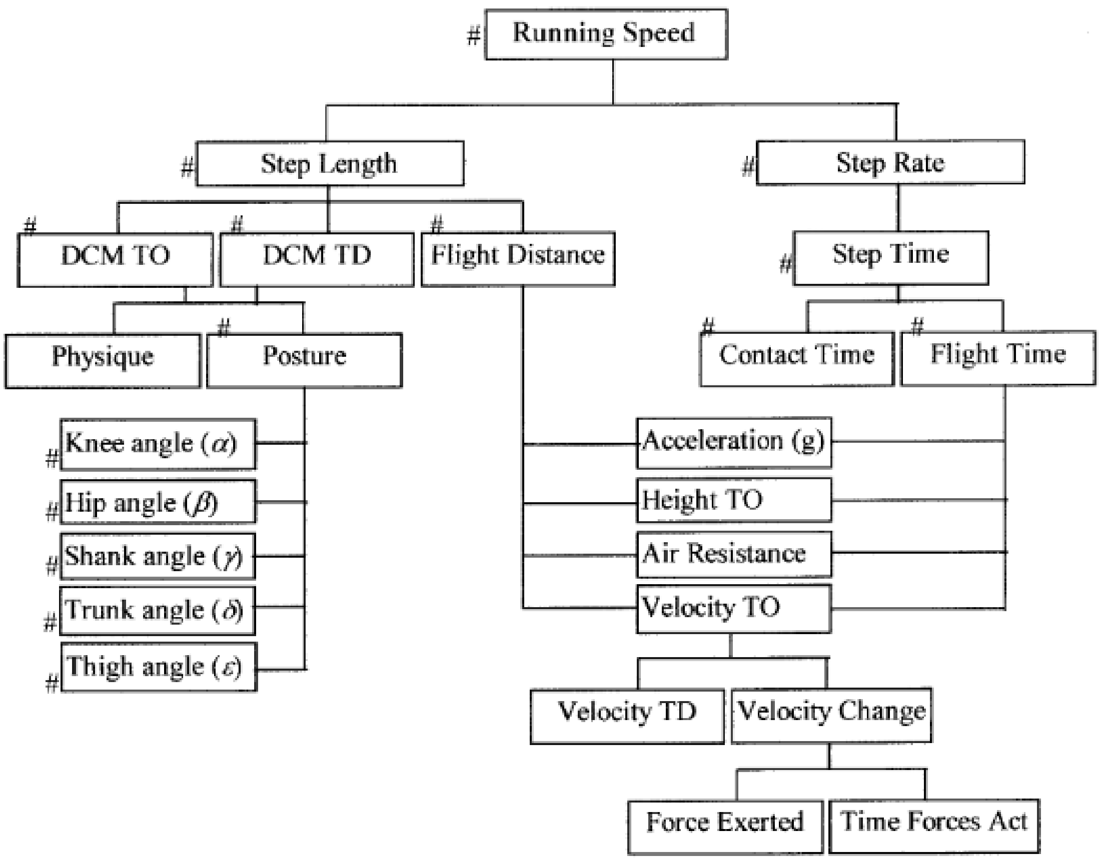


Figure 2.8. Hierarchical model illustrating the possible contribution of performance parameters to the criterion performance variable of running speed (based on Hay and Reid, 1988). DCM = the distance parallel to the running surface between a line perpendicular to the running surface which passes through the center of mass and the contact point at touchdown (TD) and take-off (TO). The '#' indicates variables directly derived from footage (*reproduced with permission from Paradisis & Cooke, 2001*).

Maximal sprint velocity has been identified as the optimal relation between SR and SL (Hay, 1993b; Čoh et al., 2001; Hunter et al., 2004). Mero and Komi (1986) reported velocity (v), SR, and SL to all increase from submaximal to supramaximal speed with values of 10.74 ± 0.37 $m \cdot s^{-1}$, 4.82 ± 0.24 Hz, and 2.23 ± 0.14 m for men; and 9.62 ± 0.23 $m \cdot s^{-1}$, 4.79 ± 0.29 Hz, and 2.01 ± 0.08 m for women. In comparison, Salo et al. (2010) reported the SR and SL of male elite athletes who competed in several major championships to be 4.71 ± 0.10 Hz and 2.20 ± 0.10 m, revealing the individuality between sprinters (Salo et al., 2011).

In major championship settings, the 1987 Rome WC reported elite men 100-m finalists achieving a minimum of 11.00 m/s, with the fastest being 11.76 m/s; elite women 100-m finalists achieved between 9.00 – 9.50 m/s, the highest being 10.75 m/s (Brüggemann & Sušanka, 1990). The 1987 study only gathered the total number of steps and average SR for the 100-m final; men between 44.6 – 47.0 steps, with a mean of 4.60 Hz; women between 45.4 – 53.0 steps with a mean of 4.50 Hz (Brüggemann & Sušanka, 1990).

The men 100-m finalists at the 1997 Athens WC reached a maximum velocity between 11.56 – 11.87 m/s, the highest being 11.87 m/s; women finalists reached a maximum velocity between 10.29 – 10.72 m/s, the highest being 10.72 m/s (Brüggemann et al., 1999). Differences were found in the temporal development of SR and SL for all finalists: within 60-100m, men finalists at 4.54 ± 0.25 Hz and 2.39 ± 0.12 m; within 30 – 60-m, women finalists at 4.59 ± 0.15 Hz and 2.15 ± 0.08 m (Brüggemann et al., 1999).

In the 2009 Berlin WC, it was reported the men's 100-m finalists achieved a mean maximum velocity of 11.88 m/s with the highest being 12.44 m/s by champion Usain

Bolt setting the world record at 9.58 s; and the women's 100-m finalists achieved a mean maximum velocity of 10.46 m/s with the highest being 10.76 m/s by runner-up, Kerron Stewart (Hommel, 2009). The Berlin report also published the number of steps taken in the race, average SR, and average SL: men finalists had 44.5 ± 2.16 steps, 4.74 ± 0.21 Hz, and 2.51 ± 0.13 m while women finalists had 49.6 ± 1.80, 4.75 ± 0.16 Hz and 2.26 ± 0.08 m (Hommel, 2009).

Finally in the most recent biomechanical analysis in a live championship setting, scientists reported mean SR, mean SL, and mean step width (SW (m)) as key kinematic characteristics of maximal velocity. The 2017 London WC revealed men 100-m finalists at men finalists at 4.74 ± 0.22 Hz, 2.42 ± 0.14 m, and 0.19 ± 0.05 m; women finalists at 4.79 ± 0.14 Hz, 2.17 ± 0.08 m, and 0.13 ± 0.08 m (Bissas et al., 2018a; Bissas et al., 2018b).

The biomechanical analysis projects listed above suggest the adoption of the deterministic model structure has brought on continued discussions around the interaction of the kinematic parameters within the model. The interaction of SR and SL has been evaluated by obtaining knowledge of the relative influence of determinants, how improvement in one is likely affected by the other, and the effect of manipulating the interaction (Hunter, 2004). Mann (2015) found performance results revealed the best tradeoff between SR and SL. Reliance on SR or SL has been found to be highly individual in 100-m sprinters (Salo et al., 2011) and a single optimal strategy does not exist during sprinting (Wild et al., 2022). Therefore, individual reliance in the context of an athlete’s training and the efficacy of technique strategies ought to be considered to inform sprint training practices (Salo et al., 2011; Wild et al., 2022). One can infer proper application of scientific principles provide a path towards minimal compromise, when possible, to sprint mechanics and optimal use of SR and SL patterns.

During the progression of SR and SL patterns, phases within one complete stride (step cycle) are important determinants to consider in maximal velocity sprinting. The two factors of the step cycle are the support (stance) phase and the swing phase. The support phase is defined as the foot being in contact with the ground, while the swing phase is the time between when the lead foot leaves the ground and makes contact with the ground again (Jiménez-Reyes, 2018). The support and swing phases reached during maximal velocity are related to knowledgeable to coaches as 'front side' and 'back side' running mechanics.

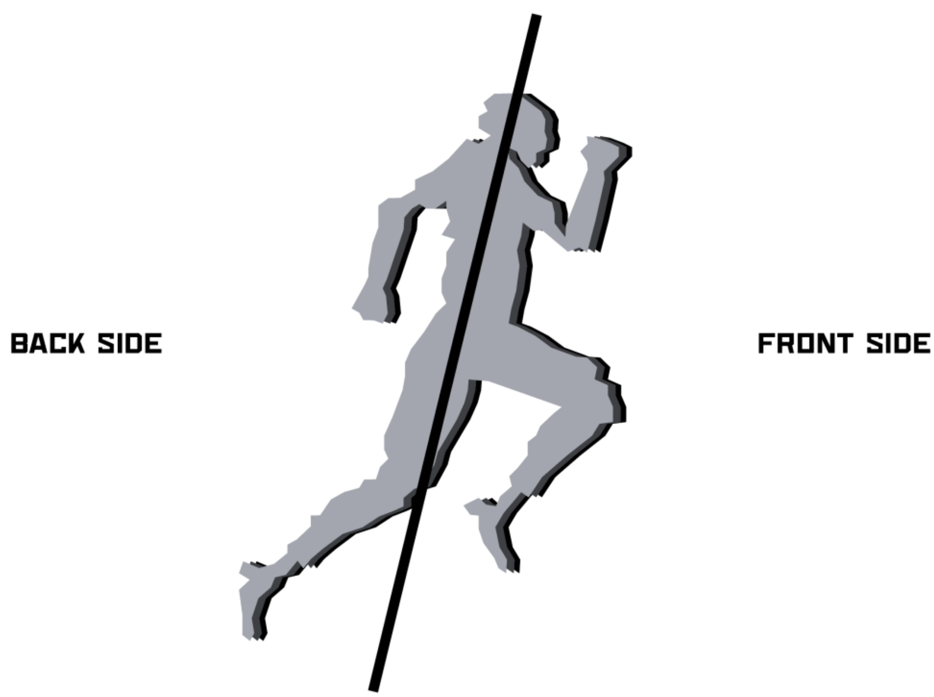


Figure 2.9. Front side and back side mechanics at maximal velocity (*adapted from Mann, 2015*).

‘Back side’ mechanics can be referred to as segments behind the body’s CM while ‘front side’ refers to segments in front of the body’s CM (Mann, 2015). The success of sprint performance can be enhanced the more a sprinter is able to shift critical ground contact efforts to the front of the body (Mann, 2015). Previous sprint investigations mentioned earlier in this review have established the importance of effective GRFs in sprint phases prior to maximal velocity. Employing the use of ‘front side’ mechanics highlights the vertical forces during ground contact on elite sprint performance at maximal velocity (Mann, 2015; Seagrave, 2009).

Upright posture is thought to benefit the ‘front side’ mechanics during the late swing, early ground contact, and production of vertical force during maximal velocity (von Lieres und Wilkau et al., 2018). In support of this notion, sprinting at maximal velocity can be characterized by maintenance in upright trunk and neutral pelvic position allowing a sprinter to reach higher knee lift position during the swing phase and a subsequent motion to “punch” the swing leg into the ground with reduced touchdown distance, higher overall leg stiffness, and a reduced support duration (Mendiguchia et al., 2022; Clark et al., 2017; Clark & Weyand, 2014). This suggests the amount of force and ground contact time made during the maximal velocity phase is predicated on how efficiently the support and swing phase generate in tandem. Weyand et al. (2010) concluded the stance phase limit on running speed is imposed not by the maximum forces the limbs apply to the ground but rather by the minimum time needed to apply large, mass-specific forces necessary (Weyand et al., 2010). Characteristics of maximal velocity are rapid ground contact time and high force application related back to SR and SL, respectively. It is important to appreciate the quality of either phase of the step cycle as dependent upon the quality of the preceding phase (Seagrave, 2009).

Along with the quality of each phase of the step cycle, Seagrave et al. (2009) emphasized the mechanics of maximal velocity to include: 1) body position, as the most central focus to be executed with a high degree of proficiency; 2) recovery mechanics, the swing phase as the first part of the step cycle where efficient mechanical recovery of the limb sets up other phases of the step cycle; 3) transition phase, a portion of the step cycle where an abrupt change in the direction of a limb is made; 4) ground preparation phase, a point where the athlete must actively prepare the foot to strike the ground; 5) ground phase, as the period composed of ‘front side’ and ‘back side’ mechanics where the athlete’s CM flight path does not change until the next application of ground force is made; and 6) arm action, where the term “drive” refers to the application of force by extension of the shoulder joint (Seagrave et al., 2009). This suggests the mechanics of maximal velocity can be analyzed and translated in phases to aid coaches in: a) being informed on the efficiency limitations their athletes have and b) what portions of technical models could be applied to increase efficiency and within performance.

In summary, although there are well-documented scientific projects of sprint mechanics in lab settings and of elite athletes in competition of select kinematic and kinetic parameters, the lack of documentation on collegiate athletes in competition necessitates investigations to understand how improvements can construct high-caliber collegiate performances. Perhaps an important question is if the observed kinematic determinants are to be considered fundamental characteristics of acceleration and maximal velocity in competition setting for college sprinters. Comprehensively examining the kinematic determinants of sprinting as it pertains to acceleration and maximal velocity is critical to the understanding of movement in high-competition environments where optimal positions are needed for effective sprinting.

2.5.2 *BIOMECHANICS OF JUMP PERFORMANCE*

The long jump to many appears to be the simplest of tasks to accomplish of the two horizontal jumps in Athletics. However, the mechanics involved in the technical aspects required before and after the board are complex in nature. The notable improvements made in the long jump have brought attention to how technique has developed and what mechanisms are being used in that development process. The following model (Figure 2.10) displays a visualization of the long jump phases.

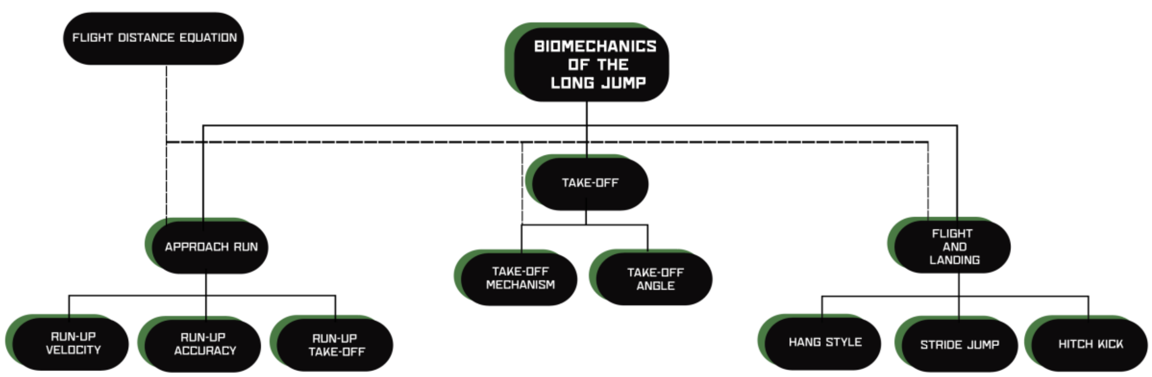


Figure 2.10. Model depicting long jump phases and associated components (*adapted from Kamnardsiri et al., 2015*).

At its core, the long jump is a measured jump set up by a run, take-off, flight, and landing. Hence, these are the four phases of the long jump. The fundamentals of the long jump demonstrate how an application of scientific principles can result in effective performances (Robison, 1974; Knudson, 2021). Factors that support whether the fundamentals of the long jump are satisfied include: 1) the run speed at the moment of take-off; 2) the force with which the body is projected; and 3) the angle of projection (Robison, 1974; Popov, 1983; Linthorne, 2008). Knowledge of the biomechanical demands of the long jump provides insight into understanding a jumper's competency in balancing the technical aspects and factors of the jump during training and competition.

Biomechanically, the long jump has been studied with the same principles related to sprinting. The application of those principles is tailored towards explaining the movements achieved during each phase of the long jump. Theoretical models have been constructed to identify the characteristics of an athlete's technique in phases leading to distances made (Hay et al., 1986; Hay, 1993).

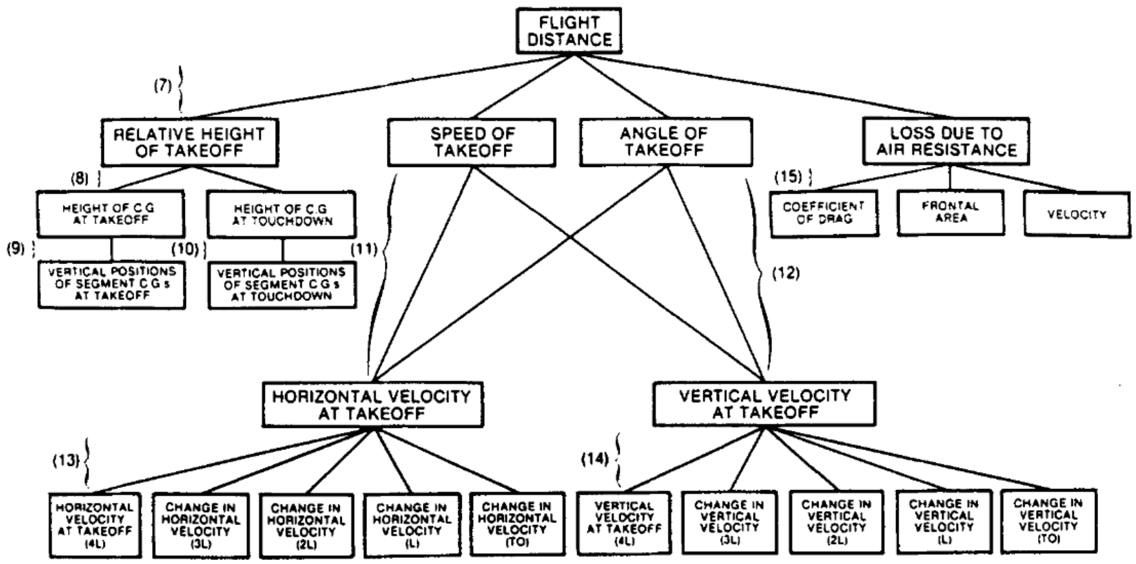


Figure 2.11. Theoretical model of factors that determine flight distance in the long jump (*reproduced with permission from Hay et al., 1986*).

Hay et al. (1986) recognized: a) the limited amount of scientific data reported on techniques used by top international class athletes; b) reports were based on only one to three trial jumps taken; c) conditions were of a non-competitive nature or non-applicable jump runways; and d) few attempts identified causal factors of performance at a high level. To address these finds, Hay et al. (1986) developed a theoretical model to best summarize the relationships between technique characteristics by describing each factor and using mathematical equations, and then applied the model to 12 male long jump finalists at the 1983 TAC U.S. National Championships. Key scientific findings included: 1) the last step (L) being shorter than the second-last (2L) step reported by previous authors; 2) horizontal velocity ranging from 10.10 – 11.40 $m \cdot s^{-1}$; 3) vertical velocities in the last four steps were small in magnitude and positive in direction; and 4) speed and horizontal velocity at take-off into the fourth-last step were all significantly related to jump distance (Hay et al., 1986). Their research suggested the need to confirm whether the results of the study were reasonably consistent and/or in agreement with past studies for further investigations to be considered.

The approach (run-up) involves acceleration, horizontal velocity, and the associated determinants in both. Characteristics such as SL, SR, support time, and visual control have been investigated to determine the effectiveness of the approach run (Omura et al., 2005). The take-off, analogous to transitioning from acceleration to maximal velocity in sprinting, involves a transfer of momentum from horizontal to vertical velocity. The jumper's goal is to create a large horizontal velocity at take-off to travel forward and a large vertical velocity giving time in the air before landing back onto the ground (Linthorne, 2008). One can infer the flight gives rise to specific styles a jumper may use to remain in the air for as long as possible—hang or hitch. This is comparable to the concept of sustaining maximal velocity once reached in sprint performances. The action taken in flight exhibits a follow-through after take-off as an aid in maintaining balance during flight and positioning the body for an effective landing (Robison, 1974; Koh & Hay, 1990). Although an athlete’s movement into the jump may cause rotation about the CM, the course of the flight is determined at the time of take-off and is unaffected by the movements (Robison, 1974). Lastly, the landing imposes on the jumper to reach forward while having control over their CM before contact is made with the sand (Koh & Hay, 1990; Linthorne, 2012). The landing movements are a consequence of transforming horizontal velocity of the approach and the resultant velocity at take-off

(Linthorne, 2012; Matić et al., 2012). The roles played by each phase in the long jump reveal the mechanisms that substantiate performance.

Coaching instruction in the long jump has been a combination of what is perceived and what literature has reported regarding technique. With the same emphasis, the lens of a coach can be further magnified through a better comprehension of the horizontal jumps. A biomechanical analysis and further discussion of the dynamics in the long jump within the Athletic performance environment promotes better functionality between what an athlete can do and what the discipline requires. This study aims to underscore the nature of long jump mechanics and its indicators through a credible scientific lens where an application of biomechanical principles can be demonstrated in coaching instruction and feedback. Limited literature is available on the phases of the long jump during collegiate competition. An investigation of these athletes in competition has the capacity to inform coaches on techniques being employed in competitive environments and improvements in the future. Of the horizontal jump disciplines, long and triple, the long jump will be the focus for the purposes of this project.

2.5.2.1 *Acceleration in Horizontal Jumps*

As the first phase in the long jump, the purpose behind the approach is to: 1) bring an athlete to the board with the toe of the take-off foot close to the front edge of the board; 2) with as much controlled horizontal velocity subsequently; and 3) with a body moving and in a position where a relatively large vertical velocity can be generated and little horizontal velocity is lost during take-off (Hay et al., 1986; Hay, 1988). Based on these concepts, the discussion of accelerative mechanisms and its relationship with the long jump should continue to be studied in competition settings at levels that precede the elite.

The development of acceleration in horizontal jump approaches is critical to performance. It demands the athlete's attention at least up until the third-last or second-last step (Hay, 1993). An athlete initiates accelerating down the runway typically in a standing position at the beginning of their approach phase. A stereotyped step pattern is produced during acceleration (Lee et al., 1982; Hay, 1988; Linthorne, 2008). Glize and Laurent (1997) describe the acceleration phase in the approach run as a stereotyped step pattern maintaining a constant impulse, thereby keeping the flight and swing-through times constant. Consistency in step patterns has been seen to occur in the first 3 – 4 steps of the approach (Jacoby, 1983; Hay & Koh, 1988). An appropriate step length coupled with an adequate step rate met during acceleration contributes to the velocity, accuracy, and preparedness needed at take-off (Hay & Koh, 1988). The step pattern must be consistent allowing the jumper to focus on their speed and the effect it will have on their jumping technique (Robison, 1974, Linthorne, 2008). Comparable to sprinting, the rate of acceleration during the approach is dependent on the SR and SL, showing the length of an approach run has a great deal to do with a jumper's ability to accelerate (Popov, 1983).

Characteristics of acceleration play a major part in key biomechanical factors influencing outcomes in long jump distance. Linthorne (2008) found a successful jumper must also be a fast sprinter with the ability to be sufficiently coordinated to perform the other phases of the long jump. Based on this, one can speculate determinant factors of performance in the long jump include generating: 1) horizontal and vertical velocity at take-off and touchdown and 2) CM height at take-off and touchdown, both shown in the performance outcome model below (Hay & Miller, 1985; Hay et al., 1986; Linthorne, 2008).

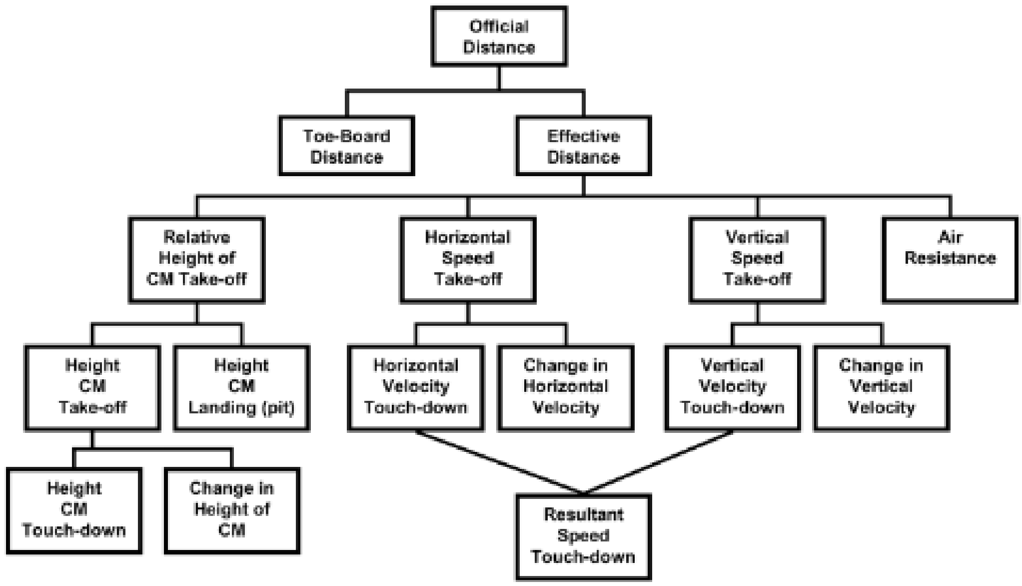


Figure 2.12. A performance outcome model of the long jump. CM = center of mass. (*reproduced with permission from Graham-Smith and Lees, 2005; this figure was based on an earlier one from Hay et al., 1986*).

From a biomechanical perspective, an understanding of these factors leads to the requirements needed in all phases of the long jump, starting with the approach and the principles behind acceleration mechanics of the approach during competition. The success of the approach run in the horizontal jumps demands requirements in accuracy, velocity, and position, as well as an athlete strategically adopting an effort towards satisfying those requirements (Hay & Koh, 1988). Studies by Lee et al. (1982) emphasized the approach having an accelerative phase where jumpers produced stereotyped step patterns along with positional errors as movement proceeded down the runway. This suggests coaches can aim to find ways to optimize the acceleration in the approach run by addressing its characteristics carried over to the next phase in competition.

2.5.2.2 *Velocity in Horizontal Jumps*

In the family of horizontal jumps, the long jump challenges the athlete to pair their approach and horizontal velocity to produce the most accurate take-off position available. An increase in the approach speed by 0.1 m/s was found to increase jump distance in the range of 0.08 – 0.10 m and even 0.12 m in some instances (Hay, 1986). It can be inferred that the way in which the approach speed is biomechanically expressed by the athlete is paramount to what is done upon arrival to the board.

Linthorne mentions a longer approach is not typically employed by jumpers that give 100% sprint speed because the advantage one has with a faster run-up speed outweighs the increased difficulty in accurately hitting the take-off board (Hay, 1986; Linthorne, 2008). Starting from a standing start, longer approach runs have been noted to be used by sprint-type jumpers to build velocity with maximal SR, therefore showing velocity prior to take-off is not only achieved by SL (Popov, 1983; Linthorne, 2008). Hay supports this notion in stating an increase in SL is effectively ruled out by the need to place the take-off foot accurately on the board and opting to achieve an acceptable SR to increase speed (Hay, 1986). Based on this, a change in the rhythm of the approach run or a loss in velocity to over-emphasize preparation for take-off should not be made (Popov, 1983; Schmolinsky, 1983; Hay & Nohara 1990). This warrants further examination of horizontal velocities achieved in competition in the last steps into the take-off board.

Horizontal velocities have been studied in the last steps leading into the take-off board. Studies have shown in the last 4 steps elite men to be in the range of 9.80 – 11.40 $m \cdot s^{-1}$ while elite women to be in the range of 8.50 – 10.00 $m \cdot s^{-1}$ (Hay & Miller, 1985; Hay et al., 1986; Hay & Nohara, 1990). Studies have also exhibited the correlations and impact horizontal velocity has on long jump distances. Horizontal velocity of the approach, center of mass at touchdown, and jump distance have consistently yielded coefficients between 0.7 – 0.9+ range (Hay et al., 1986; Hay & Nohara, 1990; Hay, 1993).

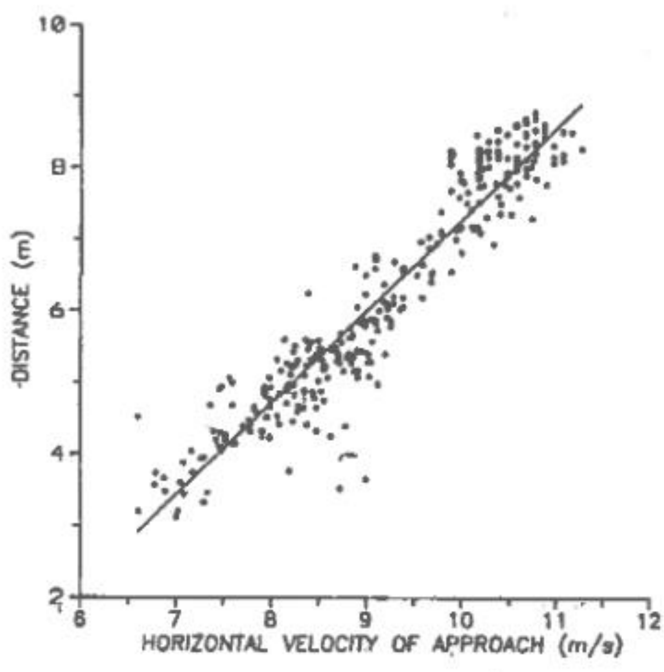


Figure 2.13. The horizontal velocity of approach vs. the official distance of the long jump for 306 jumps by 39 male and 28 female long jumpers (r = 0.95; y = 1.28x – 5.53) (*reproduced with permission from Hay, 1993*).

Quantified in major championship series and the 1984 Olympic Games, skilled jumpers did not reach maximum horizontal velocity at any point during the approach and especially even with 4 – 5 steps remaining to the board (Hay, 1986; Hay 1993a). The best jump results came from an approach with an intense beginning and maintenance of horizontal velocity in the middle of the run (Hay, 1986). These findings were evident by Hay and Miller in their analysis of the 12 female long jump finalists at the 1984 Olympic Games aimed at describing selected characteristics of jump techniques used from the approach to take-off (Hay & Miller, 1985). Mean horizontal velocities of the approach at take-off into last four steps were 9.25 m/s (fourth-last), 9.24 m/s (third-last), 9.37 m/s (second-last), and 8.82 m/s (last) (Hay & Miller, 1985), concluding the greater the horizontal velocity at take-off into the fourth-last step, the greater the distance of the jump (Hay & Miller, 1985).

In WC competition, researchers reported velocity for the best jump attempt or the mean velocity for the last steps into the take-off for men and women. The 1987 WC revealed a mean velocity of 10.94 m/s (fourth-last), 10.85 m/s (third-last), 10.93 m/s (second-last), 10.67 m/s (last-step) for men, while women reached mean velocities of 9.63 m/s (fourth-last), 9.60 m/s (third-last), 9.76 m/s (second-last), and 9.51 m/s (last-step) (Brüggemann & Sušanka, 1990).

In the 2009 Berlin WC, researchers reported the velocity of the last three steps of the best jump attempt for men and women. The mean velocity for men was 10.43 m/s (third-last), 10.52 m/s (second-last), 10.40 m/s (last-step); and for women was 9.40 m/s (third-last), 9.49 m/s (second-last), 9.33 m/s (last-step) (Hommel, 2009).

At the 2017 London WC, the mean change in velocity of the last three steps for men was 10.45 m/s (third-last), 10.27 m/s (second-last), 9.73 m/s (last-step); and for women was 9.40 m/s (third-last), 9.27 m/s (second-last), 8.75 m/s (last-step) concluding velocities reached on the runway were similar to those of a sprinter for men (range of 9.91 – 10.82 m/s) and women (range of 8.88 – 9.52 m/s), with the difference in a jumper having to control the same speed in approaching the take-off board (Tucker et al., 2018a Tucker et al., 2018b). This suggests a jumper can rely on their acceleration phase and a ‘zeroing-in’ phase (adjustment in stride pattern), both in favor of limiting a loss in horizontal velocity at take-off (Lee et al., 1982; Hay, 1988; Linthorne, 2008).

Zeroing-in phase (last three steps before take-off) has been described as the second phase of the approach during which the athlete adjusts his or her stride pattern to eliminate the spatial errors that have accrued during the first phase of the approach, the acceleration phase (Lee et al., 1982; Glize & Laurent, 1997). Adjustments made by the athlete in the step pattern are a resultant of SL, position, and horizontal velocity. Thus, 1) the length of the remaining five steps is adjusted to account for accumulated errors made in the previous steps; 2) the body’s position is adjusted in preparation for take-off; and 3) an attempt to increase horizontal velocity with control upon arrival at the board is made (Hay and Nohara, 1990). The adjustments serve to facilitate the ability of an athlete to develop vertical velocity during take-off without impairing a controlled horizontal velocity to the board (Hay and Nohara, 1990). This establishes how exigent the generation of horizontal velocity, but also limiting the loss of it, is important to acquiring vertical velocity during take-off.

Among the ways a jumper attempts to satisfy meeting horizontal and vertical velocities, visual perception of the board is used in the final steps into the board. Hay (1988) confirmed, in a duplication of research done by Lee et al. (1982), top jump performers adopted visual control strategies on the fifth-last step from the board. This work supports past conclusions of consistent step patterns being maintained during horizontal velocity and then regulated based on visual perception (Hay, 1988). This suggests a change from stereotyped to nonstereotyped step patterns reflects a move from acceleration to horizontal velocity in the approach. Overall, the jumper can be instructed to place an emphasis on their standing acceleration position and transition into using sprint mechanics to gather, or in other words, prepare themselves for take-off. It is unknown to the author's knowledge whether similar values of velocity are achieved in competition at the college level. It would be useful for coaches to know what trends the college level has achieved in competition relative to performance marks.

2.5.2.3 *Transition from Approach to Take-off*

Studies report during the approach, skilled long jumpers maintained normal sprinting action at least and up until the second-last step prior to take-off (Hay & Nohara, 1990; Hay, 1993). It can be inferred that making a transition from the approach to velocity to the take-off phase is necessary through an applicable transfer of horizontal to vertical velocity in the long jump. The transfer from phase to phase also indicates changes to the height in the center of gravity (CG) and position of sprint support phases occurring in the long jump (Hay, 1993; Linthorne, 2008). (*Note: For the purposes of discussion, center of gravity (CG) is synonymous to center of mass (CM or COM); CM* *will be the preferred use by the author, while CG or COM will be used if cited as such within a source being referenced.*)

The CG begins to lower in preparation for the take-off to allow upward velocity to be generated based on the presence of a vertical range of motion (ROM) (Linthorne, 2008).

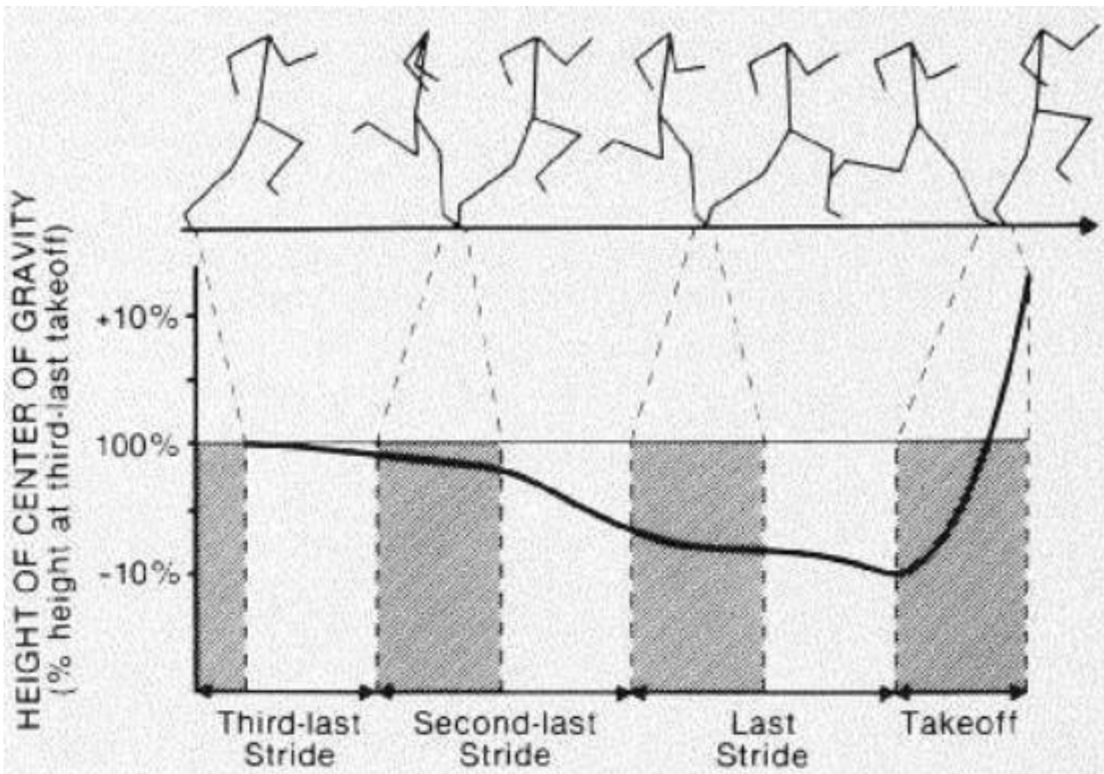


Figure 2.14. Height of center of gravity during the preparation for take-off (*reproduced with permission from Nixdorf and Brÿggemann, 1983; Hay, 1986*).

Early examinations of the long jump take-off proved to be one where resistance to forward motion is minimized, within limits set by a jumper's horizontal velocity and vertical impulse directed through CG (Dyson, 1962). Therefore, an observed lowering of CG is the jumper's attempt to preserve horizontal velocity to generate an optimal accelerative path that increases vertical velocity at take-off (Nixdorf & Brϋggeman, 1983; Brϋggeman & Sušanka, 1990; Brüggemann, 1994).

A slight lowering of CG occurs during the third-last step ('the approach height') to the following touchdown (Nixdorf & Brϋggeman, 1983; Hay and Nohara, 1990). In the second-last step, continued lowering of CG occurs during the support phase (Nixdorf & Brϋggeman, 1983; Hay, 1986; Hay and Nohara, 1990). As reported by Ter-Ovanesian, the notion in changes found in an athlete's CG path are supported by a reduction in speed over the last 5 m of the approach (Hay, 1986). Transfer of an athlete's approach velocity comes from horizontal take-off velocity (Brϋggeman, 1994; Linthorne, 2008). In combination, the degree of the 'approach height' and horizontal velocity are indicators of the technique used in the long jump (Hay & Nohara, 1990). These studies suggest a balance in the transfer of velocity and the timing of changes to CM height can influence jump distance achieved in competition.

Linthorne (2008) reported that lowering the CM while minimizing a loss in approach run velocity is practiced by long jumpers in training, to simulate what they perceive occurs in competition. It is unknown what effect the practice of lowering the CM for take-off preparation may have on competition at the college level. Past research calculated the horizontal velocity of CM by: a) dividing the horizontal displacement of CM from the first frame following take-off to the last frame before following touchdown and b) by the time elapsed between frames (Koh & Hay, 1990; Hay & Nohara, 1990). The CG height was calculated for the last three steps of the approach using: a) the frame immediately preceding the touchdown of that step and b) the frame immediately preceding the touchdown of the following step (Koh & Hay, 1990).

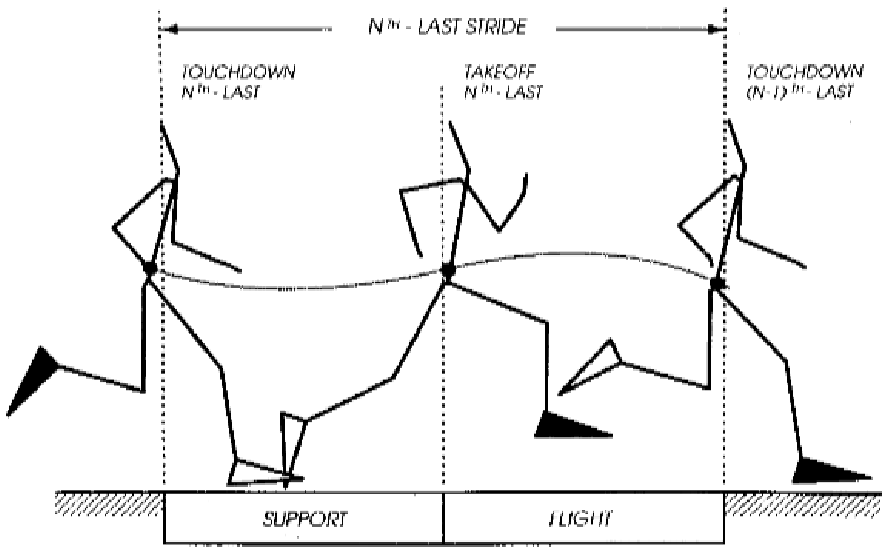


Figure 2.15. Support and flight phases of the NTH last step. Figures represent the frames taken to be touchdown and take-off, while dotted lines represent the positions of the CG at the actual instants of touchdown and take-off (*reproduced with permission from Koh & Hay, 1990*).

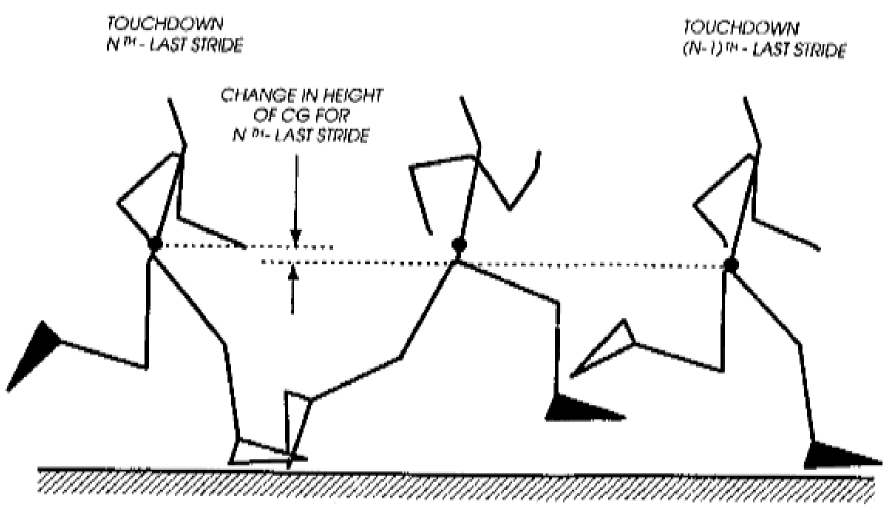


Figure 2.16. Change in height of the CG for the NTH-last step determined from the heights of the CG in the frame taken to be touchdown beginning the NTH-last step and the (N – 1)TH-last step (or jump) (*reproduced with permission from Koh & Hay, 1990*).

A study done by Koh and Hay at the 1986 and 1987 U.S. National Championships captured changes in the horizontal velocity of CG and changes in height of CG, as performance measures, of 19 elite male long jumpers adding to the scientific literature of long jump kinematics in competition (Koh & Hay, 1990). Scientists reported a mean change in horizontal velocity of 0.10 ± 0.15 m/s (second-last), -0.47 ± 0.25 m/s (last-step), and -1.20 ± 0.29 m/s (take-off); and a mean change in height of CG of 1.20 ± 2.50 m/s (third-last), -6.30 ± 3.90 m/s (second-last), and -2.20 ± 2.30 m/s (take-off) (Koh & Hay, 1990). Koh and Hay's conclusions showed: a) the mean change in horizontal velocity had an increasing trend in magnitudes; b) more was lost in successive support phases; and c) negative mean values represented a possible redirection of effort from horizontal to vertical velocity during the support phase (Koh & Hay, 1990).

Fittingly, in the same year as the 1987 U.S. National Championships, the biomechanical analysis of the 1987 Rome WC was conducted and included the long jump. Scientists pointed out the marked changes in the height of a jumper’s CM in the final steps of an approach, intended to facilitate vertical velocity at take-off (Brϋggeman & Sušanka, 1990). Of the longest attempt made by the 8 best competitors in the final, authors reported changes in CM height during support and flight phases in lieu of absolute CM height (Brϋggeman & Sušanka, 1990). For the top 8 men, the mean change of CM height during flight phases were -0.05 ± 0.02 (fourth-last), -0.03 ± 0.01 (third-last), -0.07 ± 0.02 (second-last), -0.02 ± 0.01 (last-step); with support phases being -0.05 ± 0.01 (third-last), 0.01 ± 0.01 (second-last), -0.01 ± 0.01 (last-step) (Brϋggeman & Sušanka, 1990). For top 8 women, the mean change of CM height during flight phases were -0.04 ± 0.01 (fourth-last), -0.01 ± 0.01 (third-last), -0.04 ± 0.01 (second-last), -0.02

± 0.02 (last-step); with support phases being 0.02 ± 0.01 (third-last), 0.01 ± 0.01 (second-last), -0.02 ± 0.01 (last-step) (Brϋggeman & Sus̊anka, 1990).

Scientists from the 2009 Berlin WC did not report changes in horizontal velocities or CM heights but did offer velocities reached at three critical moments of the long jump to consider: 1) instant of take-off, 2) loss at take-off, and 3) vertical velocity at take-off. In the best jump attempt analyzed, the mean for these velocities for the men were 8.78 ± 0.42 m/s, 1.62 ± 0.33 m/s, 3.53 ± 0.39 m/s whereas women set mean velocities of 7.91 ± 0.34 m/s, 1.42 ± 0.20 m/s, 3.16 ± 0.26 m/s (Hommel, 2009).

In the most recent biomechanical analysis at the 2017 London WC, scientists captured CM trajectories which included velocity components of CM at take-off along with losses in horizontal velocity during contact with the take-off board and the CM height from toe-off of the last step until take-off (Tucker et al., 2018a; Tucker et al., 2018b). Of the change in horizontal velocity (TD – TO), a mean of -1.81 ± 0.71 m/s and -1.32 ± 0.38 m/s was achieved by the 12 men and 12 women finalists, respectively (Tucker et al., 2018a; Tucker et al., 2018b). Changes in CM height were shown pictorially in an aerial perspective for each jumper, revealing key differences (e.g., CM lowering distance; highest or lowest mean last-step velocities) between medalists (Tucker et al., 2018a; Tucker et al., 2018b). These studies suggest the variance in running mechanics and techniques employed by each jumper about their penultimate step attributed to their approach. Considering all the above biomechanical studies, it is evident an understanding of the change in horizontal velocities and CM height in the transition from the approach to take-off will aid coaches in managing how these factors contribute to the success of long jump performances.

In summary, major competition analyses have provided information on the mechanical development of the long jump, techniques used, and performance trends of elite athletes. It is unknown or reported what development, techniques, or trends may exist at the college level that is familiar or foreign to the Athletics community. Biomechanical analysis of the long jump performed in competition can assist in supporting athletes and coaches in understanding the dynamics of this discipline.

2.6 ASYMMETRY

On the surface, asymmetry is the lack of symmetry between two halves or sides. Biomechanical clinical and research measures have quantified asymmetry to know what differences lie between anthropometrics, mechanics, and strength in limbs (Vagenas & Hoshizaki, 1986; Vagenas & Hoshizaki, 1991; Zifchock et al., 2007). Measurements derived from lower extremity biomechanical parameters have been aimed at gaining an accurate assessment of athletic performance, injury prevention, and rehabilitation (Carpes et al., 2010; Prvulović et al., 2022). Specifically, assessments of how limb differences affect performance based on functionality at various running speeds have become of interest to scientists. Such speeds include those generated during acceleration and maximal velocity efforts in sprint and jump disciplines.

2.6.1 *ASYMMETRY AND BIOMECHANICS*

Running is marked as a continuous task dependent on the coordinated movement of both lower extremities, thus exposing one limb to greater amounts of load than the other (Zifchock et al., 2008a; Wayner et al., 2022). It can be inferred that the response to load is reflected in how each limb functions within a given movement and the ability of that limb to perform movements under loads. This notion can be expressed as the functional asymmetry between limbs defined as the difference in the performance of movement in one limb structure compared to the other (Maćkała et al., 2021).

Scientists have reported strength asymmetries found in athletes to be attributed to consistent asymmetries and not easily interpreted due to being systematically involved in symmetric sports activities, such as sprinting (Singh, 1970; Vagenas & Hoshizaki, 1986;

Vagenas & Hoshizaki, 1991). In the findings by Vagenas and Hoshizaki, it was proposed functional bilateralism of lower extremities should be viewed as a joint or task-specific phenomenon of the human body rather than a trend of lateral dominance for one limb, given statistical significance ($p < 0.05$) in an overall trend for the left and right sides (Vagenas & Hoshizaki, 1991). This suggests scientists and coaches could assess asymmetry based on the intricacies involved in the mechanics and techniques used in sprint and jump movements.

Asymmetry values have varied based on mode of assessment and method of calculations used (Meyers et al., 2017; Zifchock et al., 2008). Modes of study have included overground running, instrumented treadmills, and gait (e.g., running, cycling) analysis, while calculation methods have included a mixture of indexes and ratios (Meyers et al., 2017; Zifchock et al., 2008). For example, a range of 0.18 – 4.33% asymmetry was found in vertical forces and spatiotemporal characteristics of sprinting performed on overground running in injury-free adults (Meyers et al., 2017). Girard et al. (2017) study described the patterns of lateralization (bilateral leg asymmetry, BLA%) in kinetic/kinematic characteristics during repeated treadmill sprints and found BLA% to be below 10.0% for all kinematic parameters (Girard et al., 2017). In a narrative review, scientists provided a synopsis of what is currently known about bilateral asymmetry in human running and cycling and its relationship to limb preferences (Carpes et al., 2010). The review also showed the number of studies supporting the notion of symmetry was limited in volume, with a large extent of research on unilateral assessment (Carpes et al., 2010). To quantify asymmetry, symmetry index (SI) has been a common method of measurement to obtain the percent difference between two limbs, which ascribes a single value to the level of asymmetry (Zifchock et al., 2008).

Although these studies have merit, research has not fully addressed the relationships between asymmetries and performance (Carpes et al., 2010), with studies having focused on populations and activities outside of the competition environment of athletes. These relationships in sprint and jump disciplines within the sport of Athletics at the college level are unknown. This suggests modes of assessment and calculation methods tailored toward competition settings have the capacity to inform athletes and coaches on how to improve performance determinants based on asymmetrical values.

2.6.2 *ASYMMETRY AND SPRINT PERFORMANCE*

Characterizing functional limb imbalances in sprint performance has been explored. A study conducted in 2012 established composite kinematic and kinetic asymmetry scores to quantify asymmetry during maximal sprint running (velocity = 9.05 ± 0.37 m/s) and found: a) variables (e.g., SR, SL, step velocity) which contributed to scores and magnitude of asymmetry varied between participants and b) new composite scores (e.g., kinematic values were small with the largest being 6.68%) for touchdown distance) indicated inter-participant differences existing in asymmetry (Exell et al., 2012b). Building upon Exell et al. (2012b) research, the same authors conducted another study in 2016 aimed to inform coaches and athletes on the use of bilateral analyses for sprint-based athletes and concluded asymmetry to be greater for kinematic variables at a high of 6.68% and magnitude of significance less than 2.5% with step characteristics less than 1.80% (Exell et al., 2016). The results reported suggested asymmetry mainly informed about study design (unilateral or bilateral analyses) and a profile of an athlete's asymmetry would be beneficial from a coaching perspective (Exell et al., 2016). It can be inferred from these studies quantifying asymmetry in sprint performance has become recognized as an important descriptor of what influences and/or may improve sprint performance.

Among skilled sprinters, dynamic lower limb strength asymmetry was established as a key determinant in optimal leg placement for sprint starts based on significant connections made between a stronger limb and higher horizontal velocities obtained (Vagenas & Hoshizaki, 1986). Study results revealed: a) skilled sprinters exhibited a significant dynamic leg strength asymmetry; b) greater horizontal take-off velocity the faster the sprint performance; and c) significantly higher horizontal and vertical take-off velocities when the stronger leg was placed in the forward position of a sprint block start (Vagenas & Hoshizaki, 1986). More importantly, the study confirmed the significance of assessing asymmetry in the leg strength of dynamic athletes and what coaching instruction could be used to direct technique changes based on assessments (Vagenas & Hoshizaki, 1986). Further steps towards understanding lower body (ankle and knee) asymmetry and performance was conducted in a study by Trivers et al., who found within elite Jamaican athletes asymmetry to be lower for 100-m sprinters in comparison to those running longer disciplines with turns, suggesting those with more symmetrical knees and ankles ran faster; that 73 of the athletes had significantly more symmetry; and confirmed past findings on ankle and knee symmetry to be positively associated with sprinting performance (Trivers et al., 2014).

With those findings on elite athletes in mind, the only known study conducted in a competition setting to the author's knowledge assessing sprint asymmetry was done during the 2017 London WC. With an incomplete body of literature on the biomechanics of sprinting asymmetry, scientists captured kinematic data of men and women 100-m finalists to assess asymmetry in the mechanics of maximal velocity (47.0 – 55.5 m) (Bissas et al., 2022). Mean asymmetry scores (SA) were based on symmetry angle (SA) valuing 0% as perfectly symmetrical and 100% as perfectly asymmetrical; were consistent between men and women sprinters at $p \geq 0.155$; and exhibited no differences at $p \geq 0.064$ and mean values of $p \geq 0.066$ between genders (Bissas et al., 2022). In addition to SA scores, a significant correlation between asymmetry and sprint performance was found in men and women for one out of 33 variables analyzed (men, foot vertical velocity pre-TD, $p = 0.006$; women, shank angle TD, $p = 0.016$); and asymmetries were quantified for men running sub-10.0 s and for women running sub-11.0 s (Bissas et al., 2022). Interestingly, asymmetry was found to not be consistent between parameters of 100-m finalists near the maximal velocity phase (Bissas et al., 2022). This study suggests, all within competition, variation exists in asymmetry within specific phases of sprinting.

Although this study adds to the literature on sprint asymmetry during elite competition, it is unknown whether these results are indicative of only elite competition or possibly sub-elite (collegiate level). Collegiate sprinters have posted sub-10.0 s and sub-11.0 s in the 100-m for men and women, respectively, at the NCAA championship meet over the last two years. An exploration of asymmetry values in sprint disciplines at the college level may provide insight for coaches to consider techniques used to improve sprint mechanics in preparation for competition.

2.6.3 *ASYMMETRY AND JUMP PERFORMANCE*

As in sprinting, the scientific literature is incomplete in describing and interpreting the relationship between asymmetry and jump performance. Establishing the relationship between asymmetry and key performance indicators is the first step to understanding what prevalence asymmetry has on measures of performance (Bishop et al., 2019; Maćkała et al., 2021).

Applied to jump tests (e.g., countermovement jump (CMJ), drop jump (DJ), standing long jump (SLJ)), asymmetry has been defined in studies as the percentage difference between limbs when values are not equal during a given task (Bishop et al., 2019; Maćkała et al., 2021). Asymmetry has also been explained as the continuity of overload on one side of the body or muscle imbalance occurring if adequate compensation is not met (Prvulović et al., 2022). Intuitively, the assumption all athletes to some degree have asymmetry is reasonable, but to what degree its presence has on and/or influences performance is unknown.

In a systematic review, the prevalence of reports on inter-limb asymmetries and their effect on performance were few with available reports indicating differences in strength potentially limiting cycling, jumping, and kicking performances, and noting the asymmetrical quantification of jump-based activities and their association with change of direction speed (Bishop, 2018a). It was concluded an understanding of the mechanisms which underpin inter-limb differences and the magnitude of performance changes occurring were potentially due to asymmetries (Bishop, 2018a), validating future exploration in sports competition.

Among elite youth female soccer players, Bishop went on to investigate the quantification of interlimb asymmetries from unilateral jump tests and its effects on speed and jump performance and found: a) single-leg counter-movement jumps (SLCMJs) to be the most appropriate jump test in identifying between-limb differences in asymmetry scores (range = 0.0 – 36.4%); b) a significant association between reduced direction specific jump performance and large asymmetries; and c) all supporting inter-limb asymmetries to be quantified and assessed with the notion asymmetries greater than 10.0% potentially impact physical and sports performance (Bishop et al., 2018b). Bishop et al. (2018b) also published a study on elite male youth soccer players, revealing larger asymmetries were associated with reduced physical performance through the quantification of inter-limb asymmetries in countermovement jumps (CMJ). Results showed: a) significant relationships being present in the effects of asymmetry on speed, change of direction, and jump performance; b) a 5.0 – 10.0% presence of asymmetry to be associated with impaired athletic performance; and c) all supporting the use of unilateral training (e.g., sprinting) beyond traditional bilateral programs (Bishop et al., 2019). These studies by Bishop et al. (2018a, 2018b, 2019) suggest coaches may look to employ training that strengthens an athlete's ability to use both limbs as uniformly as possible when doing jump-related movements. This information may aid in transferring desired mechanics needed to execute technical components of the long jump.

Maćkała et al. (2021) study had subjects perform CMJ and DJ to determine how symmetrical-single versus asymmetrical differed between men and women along with the effect each had on speed abilities. Findings included statistical significance in differences for all jump kinematic parameters in favor of men; large dispersion of the relationships between jumps and sprints based on 10-m, 20-m, and 30-m sprint runs for both men and women ($p < 0.05$); and correlation between values of height of symmetrical jumps (bilateral) and SLJ were stronger for women than men (Maćkała et al., 2021). Study findings suggest the importance of bilateral jump training to improve jump performance.

It can be inferred that the management of limb balances in disciplines where cyclic (sprinting) or acyclic (jumping) movements are employed has become important to sprint and jump coaches. A study aimed to establish differences between asymmetry and explosive strength of lower extremities derived from CMJ kinetic parameters of female sprinters ($n = 9$) showed asymmetry to be more prevalent in poorly trained athletes, a correlation with individual results, and an indicator of poor running technique (Prvulović et al., 2022). The study found a strong correlation between asymmetry and three kinetic parameters for two separate age groups (group one [15.6 ± 1.34 years] and group two [16.2 ± 1.30 years]): peak force in group one, $r = -0.878$; eccentric impulse of the left leg in group one, $r = -0.865$; concentric impulse of the right leg in group two, $r = -0.878$, ($p < 0.05$); and interestingly no correlation between asymmetry and sprint performance (Prvulović et al., 2022).

Studies have ventured into investigating asymmetry in jump and sprint performance from a gender and muscle architecture perspective. Mangine et al. (2014) examined the relationship between peak (PVJP) and mean (MVJP) vertical jump power, 30-m sprint speed (30M), and muscle architecture among recreational college-aged men and women. Scientists found: 1) muscle architecture of the thigh to be related to jumping power and sprint speed, 2) the magnitude of muscle architecture, but not asymmetry, influenced jump and sprint performance for men, and 3) for women, architectural asymmetry negatively affected jumping power and sprinting speed with muscle quality and length positively influencing jumping power and sprint speed (Mangine, et al., 2014). This suggests an understanding of the relationship between lower limb muscle asymmetry, muscle force contribution, and jump performance has merit.

These symmetrical relationships have the capacity to affect spatiotemporal values in competition. Theodorou et al. (2017) quantified and examined the influence of asymmetry of step characteristics during the approach phase of the long jump in a national athletics competition in Helsinki. Step characteristics included step length (SL), step rate (SR), and step velocity (SV). Of 10 national long jumpers, 1) the acceleration phase of the approach had a mean SL of 95.0% ± 6.0%, SR of 87.0% ± 4.0%, and a SV mean of 83.0% ± 6.0% in the late phase of the approach, 2) asymmetry of step characteristics were not consistent showing four jumpers to have significant asymmetry for SL while three jumpers had significant asymmetry for SR, and 3) there was no significant asymmetry concerning step velocity and thus no remarkable influence on take-off. It can be inferred that the relationship between asymmetry and step characteristic reliance is highly individualized.

Although the study modes and methods above have uncovered trends and interrelationships between asymmetry biomechanical factors, the nature of how asymmetry works in conjunction with competition environments has not been fully discovered. Lab-directed studies, or rather, out-of-competition environments have explored the relationship between asymmetry and performance, giving context to what coaches could consider. However, there is incomplete knowledge on asymmetry as it relates to sprinters and jumpers moving in their competitive environment and whether there is a need for symmetrical, asymmetrical, or both, in preparation for handling technical demands in competition. A biomechanical analysis touching on the investigation of asymmetry in collegiate sprinting and jumping has the capacity to perhaps confirm or refute inquiries of this subject matter.

2.7 BIOMECHANICS IN ATHLETICS

Built on the games of the ancient Olympiad, Athletics (*Track & Field*) became a global sport where all levels of talent and skill participated in a myriad of disciplines. Signature disciplines surfaced over time as popularity in the sport rose. Known to the Athletics community—athletes, coaches, spectators—signature track and field disciplines included the 100-m sprint and the long jump. These two disciplines have captivated audiences of the sport through their continued performance result milestones.

Past lab-based, out-of-competition research has tested the efficacy of interventions, monitored methodologies, and integrated clinical decision-making (Slattery et al., 2021; Haugen et al., 2019; Coutts, 2017), all providing a bases for the development of evidence-based practice in the sport of Athletics. Scientists interested in sports performance have drawn from interventions, interpretations, and approaches to create translational research for competition environments. Athletic competition settings—World Championships (WC), Olympic Games (OG), NCAA Championships (NCAA)—do not conventionally involve planned interventions or equipment use due to being perceived as potentially providing an advantage or benefit to an athlete's performance results. Sports biomechanical analyses have been executed by Athletic organizations and federations with a focus on international Athletics. As a global sport with a range of talent, skill, and development levels, a biomechanical review of scientific principles and the mechanics that explain and apply to sprinting and jumping of world-class collegiate athletes is appropriate.

2.7.1 *ELITE ATHLETICS BIOMECHANICAL PROJECTS*

Historically, researchers have developed biomechanical-driven projects to assess elite performances at WC competitions sponsored by the International Association of Athletics Federations (IAAF) (World Athletics, 2023). As participation in the sport of Athletics grew in many countries, leaders of the IAAF worked to evolve and push Athletics research forward under the vision and principles of the organization. Part of this evolution constituted supporting actions toward athlete development, coaching knowledge, and performance improvement. This effort produced performance-related literature driven by sports biomechanics, specifically related to the interpretation of competition performances and outcomes for individual Athletics disciplines for men and women.

Dating back to the 1987 WC in Rome, only finalists from IAAF federation member countries were given scientific reports with video (Brϋggeman & Suškanka, 1990). The reports disclosed biomechanical analyses of field disciplines and time analyses of track disciplines (Brϋggeman & Suškanka, 1990). The IAAF intended to not only provide analyses on performances achieved at the championships but to also assist finalists in their preparation to qualify for future championships (Brϋggeman & Suškanka, 1990). Positive reviews of the reports subsequently prompted requests from those who were not among the finalists (Brϋggeman & Suškanka, 1990). Depending on project objectives and execution plans, reports included but were not limited to: a) official meet results; b) yearly performance development in a discipline; c) calculation of select discipline parameters (e.g., acceleration, center of mass (CM)); d) comparison charts and figures of final rounds; and e) coaching commentary (Brϋggeman & Suškanka, 1990;

Brϋggeman et al., 1999; Hommel, 2009; Bissas et al., 2018a; Bissas et al., 2018b; Tucker et al., 2018a; Tucker et al., 2018b; Tucker et al., 2018c; Tucker et al., 2018d; Pollitt et al., 2018a; Pollitt et al., 2018b).

The combination of these report components being offered to finalists led the IAAF to recognize the distribution of these biomechanical analyses proved their level of commitment to the development of the sport and all its participating athletes and coaches. The presentation of reports concentrated on being in a readily understandable form, without any unnecessary scientific formulae or jargon intended to be applied immediately in training (Brϋggeman & Sušanka, 1990). The reports personified the international stage's desire to understand the movement of Athletics in championship environments by utilizing measures and processes which had the potential to support athletes and coaches most.

Fast-forward 30 years to modern-day Athletic biomechanical analyses, the IAAF now renamed World Athletics (WA), continues its mission of providing analyses to meet the sports' development and technological advances. The 2017 London WC commenced the largest biomechanical research project in Athletics by WA (World Athletics, 2018). Led by Project Director Dr. Athanassios Bissas and Project Leader Stéphane Merlino, 38 specific discipline reports with coaching commentary were produced covering the performances of over 730 athletes (World Athletics, 2018). Sprint (100-m, 200-m, 400-m) and horizontal jump (long and triple jump) disciplines were filmed and analyzed for both men and women. Following the success of those championships and the overwhelming reception of the project's ability to reach the Athletics community, Dr. Bissas and Mr. Merlino went on to conduct the first indoor biomechanical analysis in

Athletics. The 2018 Birmingham Indoor World Championships yielded 13 in-depth specific discipline reports of 161 athletes in 13 disciplines (World Athletics, 2019). The 60-m dash, long jump, and triple jump were the sprint and horizontal jump disciplines covered in these championships. Both biomechanical analyses conducted in London and Birmingham used multiple high-speed cameras to capture live footage later digitized to obtain kinematic data. The number of projects completed on the international Athletics stage signifies the impact research is having on the evolution of Athletic performance for athletes and coaches. It can be inferred that this impact on research can be made at the college level through an analysis of the highest competition setting available.

2.7.2 *COLLEGIATE ATHLETICS BIOMECHANICAL PROJECTS*

Of the 21 disciplines featured at the outdoor NCAA Championships, there are two short sprint disciplines and two horizontal jump disciplines. The short sprints for men and women are the 100-m and 200-m while horizontal jumps for men and women are the long jump and triple jump. For the purposes of this project, the 100-m and long jump will be the two disciplines researched.

To the author's knowledge, an extensive live biomechanical data collection of an NCAA Division I Track & Field Championship has not occurred. The first known study to capture biomechanical data during a live championship setting occurred in 1987 (Hay & Koh, 1988). James Hay and Timothy Koh, from the University of Iowa, collected biomechanical data on the horizontal jump disciplines for men and women at the collegiate 1987 Big Ten Conference Championships (*Note: Conference championships within the NCAA represent the division of college teams placed in competing regional* *leagues who then attempt to qualify and compete on the national level at the NCAA championships.*)

The purpose of Hay and Koh's study was to "develop measures of a long or triple jumper's ability to use programming and visual control strategies during the approach to the takeoff" (Hay and Koh, 1988). Official distance marks from 4 disciplines—men's long jump, women's long jump, men's triple jump, and women's triple jump—for only select competitor placers (1^{st}, 4^{th}, 8^{th}, and 12^{th}) were reported (Hay & Koh, 1988). Based on digitized film analysis, measures taken from the final three steps in the approach included official jump distance, horizontal velocity of CG, toe-board distance, horizontal velocity at touchdown, visual control (accuracy), visual control (velocity), visual control (position), and percentiles (Hay & Koh, 1990). Specifically, visual control (accuracy) measures were based on the number of legal jumps recorded and the mean toe-board distance at take-off into the jump; visual control (velocity) based on the correlation between toe-board distance for the support phase and horizontal velocity of CG at the instant of takeoff; visual control (position) based on toe-board distance during support phase immediately preceding the last-step of approach; and percentiles based on the relationship between the measures of programming and visual control ability (Hay & Koh, 1990).

The authors describe a successful approach run in the horizontal jump disciplines requiring three factors: takeoff foot accuracy, velocity, and body position (Hay & Koh, 1988; Hay, 1993). Hay drew from his previous work in which he studied the approach runs of 47 elite male and female long jumpers to determine whether visual control strategies were used. Study findings led authors to believe adoptive visual control strategies were needed to satisfy approach run requirements (Hay & Koh, 1988). To explore programming and visual control strategies in Athletics, two high-speed 16mm cameras were used to capture jump attempts in live competition. Digitizing covered 21 points defined by a 14-link model (Hay & Koh, 1988). Study results revealed an "…interpretation was largely subjective, repeated uses of study procedures suggested ways to reduce subjective elements, the measures selected were based on logic and available research, and for the time being provided a starting point for addressing this issue with jumpers…" (Hay & Koh, 1988). Hay & Koh's research acknowledged the success of horizontal jump disciplines dependent on satisfying three requirements. The requirements were an approach velocity (m/s), position (x), and takeoff (m or ˚) at specific points during the competition (Hay and Koh, 1988). Based on these competition environment methods and measures, studies of this nature suggest the championship performance profiles which could be created to better understand movement in competition.

To date, other semi-related performance projects of U.S. collegiate sprinters and jumpers have been staged in out-of-competition controlled lab settings with research interventions (e.g., dynamic warm-up, supplements) and/or wearable equipment (e.g., resistance sleds). Sha et al. (2014) examined kinematic variables related to Division-I male sprinters. Kinematic data were collected to determine the relationship between the magnitude of center of mass (CM) acceleration during braking and propulsion phases in maximal speed sprint performance (Sha, 2014). Two maximal 60-m dash trials under non-competitive race conditions were measured in a controlled indoor facility using Vicon Nexus motion capture and an electronic timing gate system. Requiring markers, a motion capture system was used to collect full-body kinematic data. Researchers found of the 12 sprinters, some generated greater positive acceleration during the propulsion phase while compensating for negative acceleration during the braking phases (Sha, 2014). The authors also confirmed minimal braking phases during sprint performance decreases a loss in horizontal velocity. This study suggests an attempt at simulating speeds achieved in race conditions offers information on what kinematic values may contribute to performance and what values may inform on how to improve preparation for competition.

2.8 LIMITATIONS OF PREVIOUS RESEARCH

Limitations of past biomechanical studies conducted in- and out-of-competition settings have focused primarily on elite athletes. Lab-based or simulated sprint or jump training environments have studied non-elite or recreational athletes. Based on the objectives of previous biomechanical studies, it has not been confirmed what factors influence performance in select Athletic disciplines on the collegiate championship stage.

Although World Athletics (WA) has produced biomechanical reports on international championships in the last 30 years, all reports from this governing body:

- Did not provide individual profiles for each athlete.
- Did not analyze all sprint and jump disciplines contested.
- Did not provide coaching commentary for future considerations by the athletics community.
- Did not evaluate the same parameters in each report, although there were many commonalities (e.g., stride length (SL), step rate (SR)).

2.9 RATIONALE FOR CURRENT PROJECT

Sprint and horizontal jump disciplines have historically been studied in phases. Delecluse et al. (1992) proposed “good performances in one phase will not guarantee good performances in other phases” (Delecluse, 1992). This suggests an understanding of Athletic discipline phase determinant factors and their associated kinematic parameters provides coaches with: 1) invaluable information about the implications these factors have on performance in a training or competition setting and 2) the ability to monitor a litany of talent to improve discipline requirements.

Although a plethora of studies and reviews have been done on sprinting and jumping, the literature is incomplete in examining factors of acceleration, maximal velocity, and asymmetry in the sub-elite (college) championship setting. These determinants have been shown to be associated with Athletic discipline performances. Scientists have contributed to the literature thus setting a standard in how elite competition can be assessed and interpreted. This standard has yet to exist at the college level, where great strides in the development of athletes as young adults in the sport can be made. To support the coach’s position and an athlete’s potential, the aims of this project have applied similar WC methodologies to the NCAA championship competition to obtain informative performance data about the college athlete population. Thus, this project has created and updated the database for biomechanical parameters on sub-elite (collegiate) athletes.

This project aspires to contribute an analysis of Athletic performance driven by evidence-based practices to impact the translation and utilization of biomechanical competition data for future preparation. Proper application and practical value are rooted in understanding why short-term preparation must run parallel with the long-term development of an athlete. A biomechanical analysis of select sprint and jump disciplines offers an understanding of performance leading to significant practical implications for coaches to draw upon for ideal practices in athlete development. Furthermore, an analysis presents important trends in technical development and conditions in which top performances may be reached.

The production of biomechanical reports on major championships, such as NCAA championships, pushes forth the development of athletes, coaching philosophies, and techniques that support the mechanics involved in Athletic disciplines, from the practice fields to the competition grounds. There is an opportunity for comparisons of biomechanical performance data between college athletes. The sports narratives of the coaching and scientific fields have the capacity to be enriched by this project building upon the authenticity of world-class sprint and jump athletes in the most highly competitive conditions outside of the Olympic Games and World Championships in Athletics.

Chapter 3
METHODS

3.1 INTRODUCTION

This chapter provides details regarding the procedures used to conduct this project. Information related to participants, equipment, and setup is included. Biomechanical collections of major championships date back to the second WC in 1987 and have carried over to subsequent elite championships. This project draws upon the methodological framework seen and used internationally at WC and applied to the current landscape of the NCAA's Track & Field (*Athletics*) championships held in the U.S.

On the college stage, 21 disciplines are contested at the NCAA Track & Field Championships. Men & women both compete in the short sprints (100-m, 200-m) and horizontal jumps (long jump, triple jump) at the championships. This project focuses on women competitors in the 100-m and long jump at the 2021 NCAA Track & Field Championships, held at Hayward Field in Eugene, Oregon, USA. (*Note: Logistical planning and collection of the project adhered to COVID regulations and restrictions at these championships.*)

3.1.1 *PAST BIOMECHANICAL METHODS*

Past biomechanical data collections at live major championships have provided important guiding details concerning methods used for video capture, camera location, and calibration methods. Among popular World Athletics driven projects:

- 1987 Rome WC, being the first biomechanical collection at a world championship, conducted a three-dimensional analysis of sprint (100-m, 200-m, 400-m), hurdle (100-mH, 110-mH, 400-mH), horizontal jump (long jump, triple jump), vertical jump (high jump, pole vault), and throw (shot put, discus, javelin, hammer) disciplines for men and women (Brϋggeman & Sušanka, 1990).
- 1997 Athens WC was a three-dimensional biomechanical analysis of sprinting (100-m, 200-m, 400-m), hurdle (100-mH, 110-mH, 400-mH), jumping (long jump, triple jump, high jump, pole vault), and throwing (discus) disciplines; the project focused on the men and women finals in all disciplines listed except the 400mH (Brϋggeman & Sušanka, 1990).
- 2007 London WC was the largest ever biomechanical collection producing 38 discipline reports on sprint (100-m, 200-m, 400-m, 4x100-m Relay), middle distance (800-m), distance (1500-m, 5000-m, 3000-m steeplechase, 10,000-m), hurdle (100-mH, 110-mH), horizontal jump (long jump, triple jump), vertical jump (high jump, pole vault), and throw (shot put, discus, javelin, hammer) disciplines for men and women; three-dimensional and time analyses were conducted on specific disciplines (Bissas et al, 2018a; Bissas et al, 2018b; Tucker et al., 2018a; Tucker et al., 2018b).

3.2 PARTICIPANTS

Data were collected from the Eugene 2021 NCAA Track & Field Championships and archived NCAA championships over the last decade. For educational purposes, the use of archived video data was approved by the NCAA, who owns and controls the data in partnership with Veritone. This permission was sought out for the project to proceed in the midst of the pandemic. Non-archival footage remains under the ownership and control of the University of Oregon. The study was approved by the University of Oregon and research compliance service procedures under the pre-2018 Common Rule and determined to qualify for exemption given the nature of the study.

The temperature, wind, humidity, pressure, and altitude were 78°F, 0 mph NE, 52%, 29.80in, and 470ft for the women's 100-m and 65°F, 2 mph WNW, 56%, 30.09in, 470ft for the women's long jump (Jank & Jennings, 2023). For analysis, the first round, quarterfinalists, and semifinalists of the 100-m were analyzed in two-dimensional detail, while the 9 finalists in the women's 100-m final were analyzed in three-dimensional detail; the first round and preliminary round jumpers were analyzed in two-dimensional detail, while the top 7 finalists in the women's long jump final (due to being in the same flight on the same runway) were analyzed in three-dimensional detail. Both discipline rounds were contested on the evening of the 10th and 12th of June 2021 at Hayward Field.

For the 100-m, the championship format anticipated a minimum of n = 24 for the semifinal start list (contested in 3 heats of 8 competitors), 9 advancing to the final (top 2 in each heat plus the next 3 best times). Competitors represented 18 NCAA member institutions. Headed into the final two rounds of championships in Eugene, the collegiate competitive experience included 0 to 4 years for semi-finalists and finalists, with national season ranking ranging from 1 – 33 in the country. Season-best (SB) and personal best (PB) times for 9 finalists were 11.04 ± 0.02 s and 11.05 ± -0.01 s, (mean ± standard deviation), respectively.

For the long jump, a minimum of $n = 24$ were slated to compete in 2 flights of 12 for 3 attempts (Preliminary Round 1, Round 2, and Round 3), 9 advancing for 3 more attempts (Final Round 4, Round 5, and Round 6). Competitors represented 17 NCAA member institutions. Headed into the final two flights of the championships in Eugene, collegiate competitive experience also included 0 to 4 years for semi-finalists and finalists, with national season rankings ranging from 1 – 64 in the country. Season-best (SB) and personal best (PB) marks for 9 finalists were 6.77 ± 0.19 m and 6.77 ± 0.19 m, respectively.

3.3 FACILITY

Hayward Field track surface was a synthetic Beynon Sports Surface BSS-2000 covering 9 lanes and field event areas (Lawson, 2020; Beynon, 2023). The lanes were 1.067 m wide and 5 cm apart from each other and bordered by a 5 cm inside curb (NCAA, 2021). The same track surface covered the jump runways 1.22 (± 0.01) m wide with 1.21 x 0.20 m wood take-off boards (NCAA, 2021). The facility, per NCAA and World Athletics rules, met requirements for approved sanctioned national and international major competitions.

3.4 DATA COLLECTION

Five prime locations for camera placement in the upper level of Hayward Field were identified and secured spanning from slightly behind the start of the 110-m men's high hurdles, down the home straight away, and into the first turn, as depicted in Figure 3.1 below. Data were collected for lanes one through nine in the 100-m and on the west runway closest to the track for the long jump.

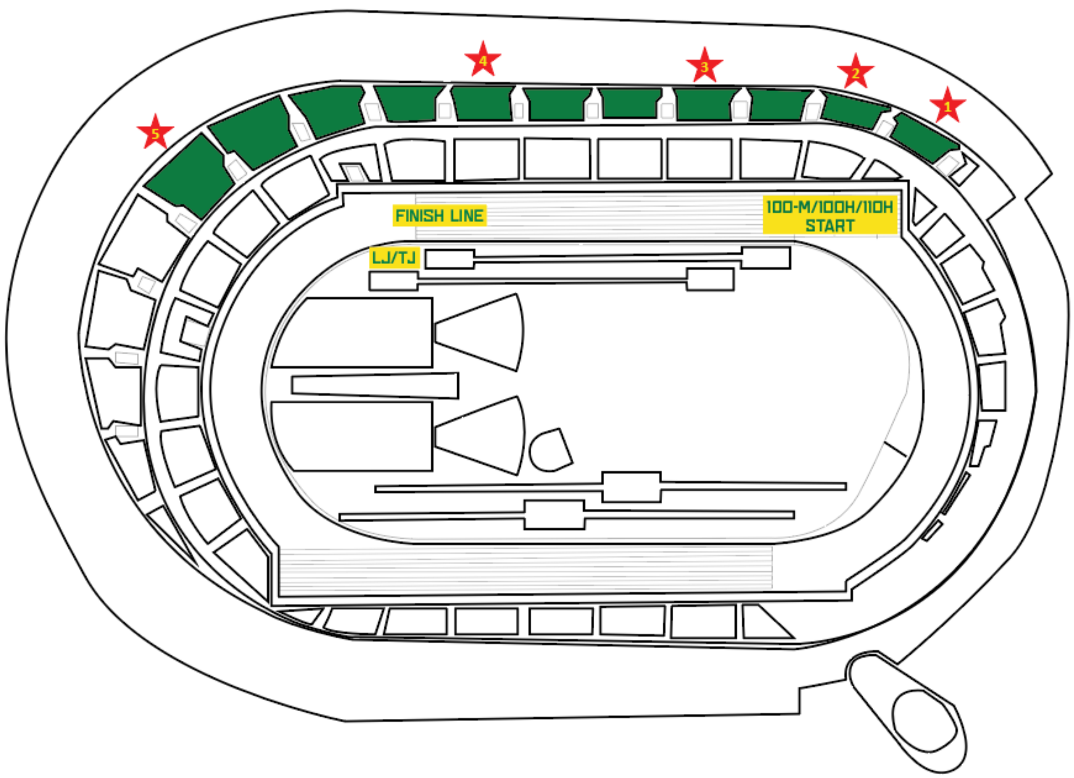


Figure 3.1. Camera placement for the Women's 100-m and long jump at the 2021 NCAA Championships (*ariel view of Hayward Field courtesy of UO Athletics, reproduced and adapted by author*).

A total of 12 high-speed cameras were obtained for data capture, but one camera was found to be inoperable. Five Sony PXW-FS7 cameras and six Sony PXW-FS5 cameras were used to capture the motion of athletes during the acceleration (13 – 20-m), maximal velocity (40 – 47-m), and runway approach (last 10 m back from the front edge of the jumping pit) phases. Each camera was mounted on an individual adjustable quality aluminum tripod. On the first day of competition, the 100-m semi-finals and long jump flights and finals were held during the same time, while on the second day of competition, only the 100-m finals were held. To navigate the competition schedule, for day one, seven cameras captured designated phases in the 100-m, and four cameras captured the long jump; and for day two, all cameras were employed to capture designated phases in the 100-m.

3.5 CALIBRATION

Based on the championship schedule, broadcast timetable, and facility access, calibration procedures were conducted before the start of each day of competition. Rigid cubic calibration dimensions (x, y, z) were 3.350 x 3.350 x 3.350 m, comprising 60 control points that were used. The calibration frame was custom-built by the researcher using PVC fittings and pipe products with points defined by black cross sections marked with reflective markers, as shown in Figure 3.2.

The rigid cuboid calibration frame was positioned on the track and runway aligning with track lane marks. Each phase (acceleration and maximal velocity) of the 100-m was calibrated in a sequential order based on the width along and across from lanes 1 to 9. The approach phase for the long jump was calibrated in a sequential order based on the width of the runway from the edge of the jumping pit moving up the runway. Both calibration processes were done to accurately define the volume of space athletes would accelerate through, reach optimal maximal velocity, and prepare for take-off during the 100-m and long jump, respectively. The result of these processes constructed a bi-lane and runway-specific global coordinate system for each discipline based on a large quantity of non-coplanar control points given a calibrated volume space.

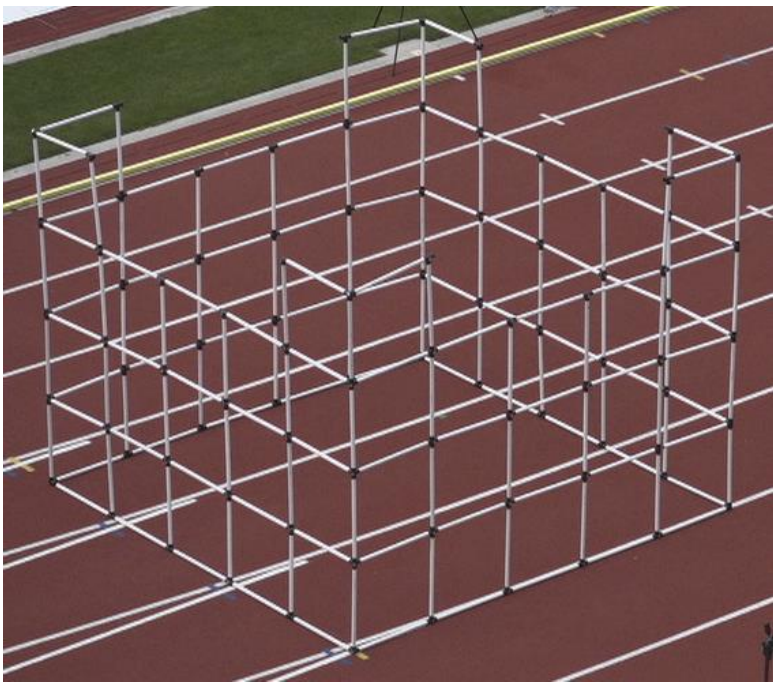


Figure 3.2. The calibration frame was constructed and filmed prior to the start of competition.

3.6 CAMERA PLACEMENT

Cameras were placed in secure locations within the stadium accessible to camera operators at optimal semi-sagittal, sagittal, and frontal angles of designated phases for the 100-m and long jump disciplines. Of the five prime camera locations on day one of the women's competition, the acceleration phase was captured using locations 1, 2, 3, and 5; the maximal velocity phase was captured using locations 2, 3, and 4; and the runway approach was captured using locations 2, 3, 4, and 5. On day two, the acceleration phase was captured using locations 1, 2, 3, and 5; and the maximal velocity phase was captured using locations 2, 3, 4, and 5.

Figure 3.3 below shows the configuration for the designated acceleration phase.

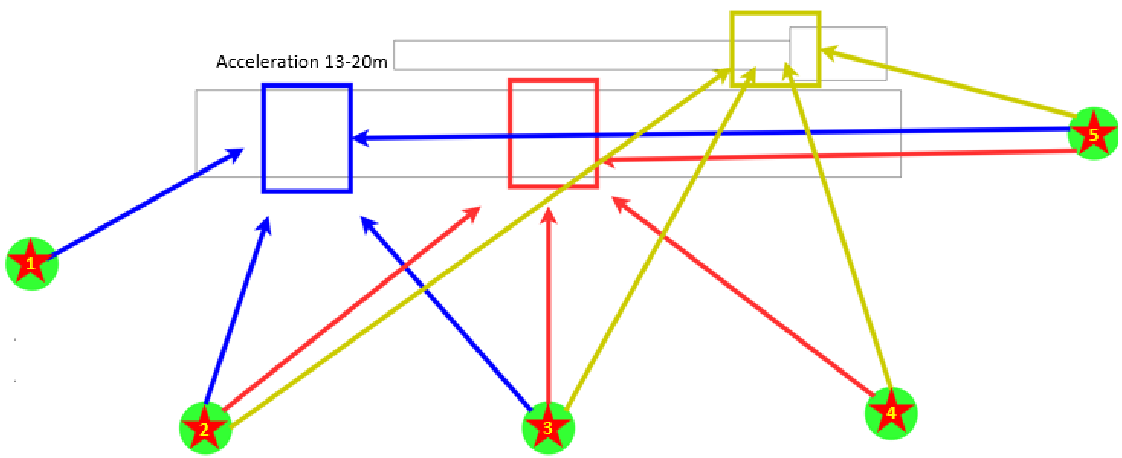


Figure 3.3. Camera layout and captured volume for acceleration phase in the Women's 100-m discipline at the 2021 NCAA Track & Field Championships.

Figure 3.4 below shows the configuration for designated maximal velocity phase.

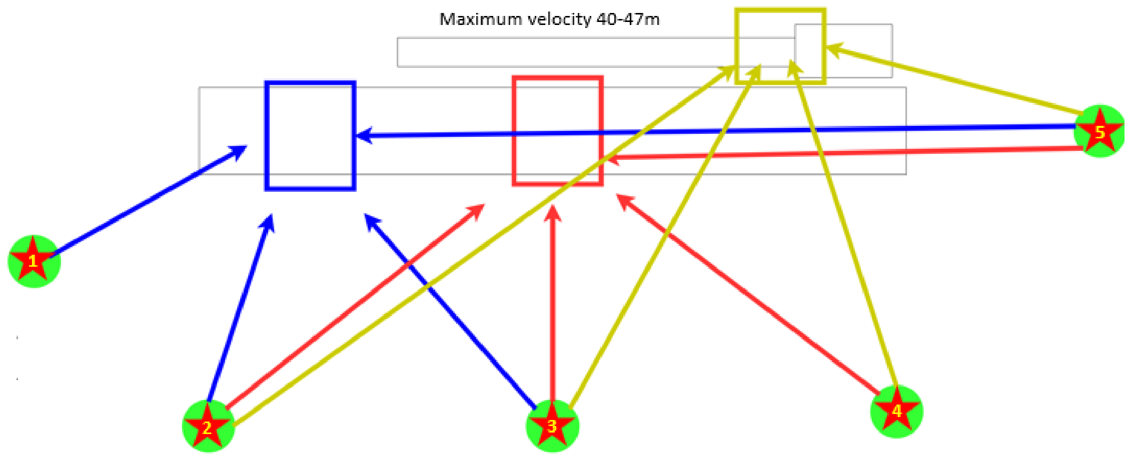


Figure 3.4. Camera layout and captured volume for maximal velocity phase in the Women's 100-m discipline at the 2021 NCAA Track & Field Championships.

Figure 3.5 below shows the configuration for the designated long jump runway approach phase.

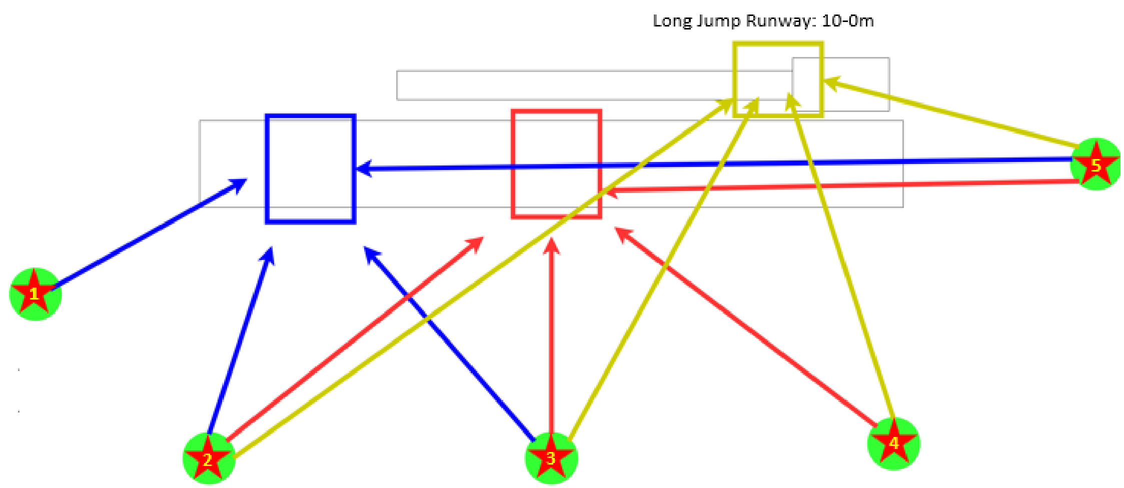


Figure 3.5. Camera layout and captured volume approach phase for the Women's long jump discipline at the 2021 NCAA Track & Field Championships.

3.7 DATA RECORDING

Based on project objectives, the number of cameras employed for biomechanical collections can vary among scientists. For the aims of this project, camera selection and position were set to purposefully capture components of acceleration, maximal velocity, and preparation prior to take-off. Recording settings were chosen due to past studies and outdoor competition conditions concerning weather and stadium lighting.

On the first day of the Women's competition, seven cameras were employed to record the action of the Women's 100-m semi-finals. Five Sony PXW-FS5 cameras operating at 200 Hz (shutter speed: 1/1750 s; ISO: 2500; FHD: 1920 x 1080 px) and one Sony PXW-FS7 camera operating at 150 Hz (shutter speed: 1/1250 s; ISO: 1600; FHD: 1920 x 1080 px). Table 3.1 summarizes the camera settings used.

Camera	Operating (Hz)	Shutter Speed	ISO	FHD Pixels (px)
SONY PXW-FS5	200	1/1750	2500	1920x1080
SONY PXW-FS7	150	1/1250	1600	1920x1080

Table 3.1. Camera recording setting for motion in designated 100-m and long jump phases.

To capture acceleration and maximal velocity phase at the same time, four Sony PXW-FS5 were designated for the acceleration section, whereas two Sony PXW-FS5 and one Sony PXW-FS7 were designated for the maximal velocity phase. Due to all rounds (1 through 6) of the long jump being contested during the semifinals of the 100-m, four Sony PXW-FS7 were designated to capture the approach phase for the long jump.

On the second day of the Women's competition, eleven cameras were employed to record the action of the Women's 100-m final. Four Sony PXW-FS5 and one Sony PXW-FS7 were designated for the acceleration phase, whereas two Sony PXW-FS5 and four Sony PXW-FS7 were paired for the maximal velocity phase.

3.8 DATA PROCESSING

All sprint and jump footage captured live during the championships were imported into SIMI Motion (SIMI Motion version 10.2.0, Simi Reality Motion Systems GmbH, Germany). Kinematic data were obtained through manual digitization of video files by a single qualified operator. To synchronize the two-dimensional coordinates from each camera, an event synchronization technique was used through SIMI Motion.

To provide padding during filtering, digitizing started and ended with 15 frames before and after a stride was completed. Each file created was digitized frame by frame for each joint. Adjustments were made as needed using a point-over-frame method in which each point (e.g., left ankle joint) was tracked through the entire sequence. In line with de Leva's body segment parameter models (de Leva, 1996), a 17-point whole-body model was used to create the whole-body center of mass (CM) for each sprinter and jumper. The 17 anatomic locations based on 14 segments included the head, left and right sides of the shoulder, elbow, wrist, finger (metacarpophalangeal (MCP)), hip, knee, ankle, and foot (metatarsophalangeal (MTP)) joints.

Three-dimensional (3D) coordinates were reconstructed from each individual camera's x and y image coordinates using Direct Linear Transformation (DLT) algorithm (Abdel-Aziz & Karara, 1971; Abdel-Aziz & Karara, 2015). DLT is a technique commonly used by scientists to calibrate cameras and subsequently reconstruct control points from two or more two-dimensional cameras into three-dimensional objects in space to assess the accuracy of reconstruction (Abdel-Aziz & Karara, 1971; Challis & Kerwin, 1992; Chen et al., 1994; Bezodis et al., 2019).

The reliability of the digitizing process for the operator (author) was assessed using a repeated process done within a 48-hour period. Specific variables (e.g., head, shoulder, knee, right MTP) were chosen for three randomly selected athletes. ICC (intraclass correlation coefficient) and RMSD (root mean square deviation) values confirmed high reliability, minimal systematic and random errors in the digitization process.

Analysis	100-m Acceleration Phase (Hz)	100-m Maximal Velocity (Hz)	Long Jump Approach phase (Hz)
Digitizing [3D]	200	150	150
Temporal [2D]	200	200	150

Table 3.2. Two- and three-dimensional frame rates used for each phase obtained in the 100-m and long jump.

Raw coordinate data obtained from the manual digitizing were filtered with a recursive second-order, low-pass Butterworth digital filter (zero phase-lag) whilst a residual analysis was used to calculate cut-off frequencies for each digitized point (Winter, 2009). Temporal kinematic characteristics were processed and calculated using a hybrid frame time, obtained via an inter-frame interpolation technique.

All archived footage was imported into Dartfish 11.2 for select spatiotemporal two-dimensional (2D) analysis.

3.9 ANALYZED VARIABLES

Performance of athletes were characterized by select variables listed in Table 3.3 and 3.4. The following spatiotemporal variables were extracted from the digitized data to construct kinematic signatures for each athlete. The range of variables mirror those employed by Bissas et al., (2018a and 2018b), and are considered sufficient and appropriate for this type of analysis as they offer a) information about direct performance characteristics (e.g., contact time, step rate, velocity) and b) insights into biomechanical characteristics governing the observed performance (e.g., CM variables, segmental angles).

Table 3.3. Short sprints – 100-m variables

VARIABLE	DEFINITION
Contact time	The amount of time a foot remains in contact with the ground.
Flight time	The amount of time from toe-off (TO) of one foot to touchdown (TD) of the other foot.
Step count [#]	The number of steps taken in a defined area.
Step rate [*Hz*]	The rate at which foot contacts are made per second.
Step length [*m*]	The distance between each foot contact from one toe-off to the next toe-off
Step width [*m*]	The mediolateral distance made between one-foot contact to the next.
Step time [*s*]	The sum of contact time and flight time.
Swing time [*s*]	The amount of time a foot is not in full contact with the ground in one complete stride.
Acceleration [m/s^2]	The change in velocity over time.
Maximal velocity [*m/s*]	The product of step rate and step length.
Step velocity [*m/s*]	The step length divided by the step time.
Velocity [*m/s*]	The displacement distance over time.

Center of Mass [*CM*]	The point about which an athlete's mass is balanced.
DCM TD [*m*]	The horizontal distance between CM and ground contact of foot tip at touchdown (TD).
DCM TO [*m*]	The horizontal distance between CM and ground contact of foot tip at toe-off (TO).
CM contact distance [*m*]	The horizontal distance CM travels during a single ground contact.
CM height [*m*]	The vertical distance between CM and the track surface during ground contact.
CM horizontal velocity [*m/s*]	The mean horizontal CM velocity over one step.
CM vertical velocity [*m/s*]	The vertical component of the CM velocity during ground contact.
Foot horizontal velocity [*m/s*]	The horizontal component of the foot's CM velocity.
Foot vertical velocity [*m/s*]	The vertical component of the foot's CM velocity.
Resultant foot swing velocity [*m/s*]	The resultant linear velocity of the foot's CM during the swing phase.
Braking phase	The amount of time the CM is in the downward phase during ground contact.
Propulsive phase	The amount of time the CM is in the upward phase during ground contact.
Trunk angle [α]	The trunk angle relative to an upright anatomical position at 90˚.
Knee angle [β]	The angle between the thigh and shank (lower leg) relative to 180˚ in anatomical position.
Ankle angle [ι]	The angle between the shank (lower leg) and the foot.
Contact leg hip angle [γ]	The angle created by the shoulder, hip, and knee of the foot in contact with the ground.
Minimum knee angle (°)	The lowest knee angle reached up full foot ground contact.
Δ Knee angle (°)	The difference between knee angle at touchdown and minimum knee angle.
Minimum ankle angle (°)	The lowest ankle angle reached up full foot ground contact.
Δ Ankle angle (°)	The difference between ankle angle at touchdown and minimum ankle angle.

From the 100-m sprint variables listed above, a focus was made on horizontal sprint variables and postural characteristics of a step cycle during acceleration and maximal velocity.

Table 3.4. Horizontal jumps – long jump variables

VARIABLE	DEFINITION
Official distance	The distance published in the official final competition results.
Effective distance	The measured distance from the tip of foot on take-off relative to take-off from the board, including the official distance.
Take-off loss	The distance from the tip of foot on take-off relative to take-off board.
Step length (up to last 4 steps)	The length of the approach steps from foot tip of one step to the next foot tip.
Change in step length (up to last 4 steps)	The difference in length between each step in a percent.
Step width (up to last 4 steps)	The displacement from toe-off of one foot to the next side-to-side.
Contact time (up to last 4 steps)	The amount of time spent on the ground during the support phase of up to the last 4 steps.
Velocity of 4 last steps [*m/s*]	The horizontal velocity measured during the last 4 steps of an approach run to the take-off board.
Velocity of 3 last steps [*m/s*]	The horizontal velocity measured during the last 3 steps of an approach run to the take-off board.
Velocity of 2 last steps [*m/s*]	The horizontal velocity measured during the last 2 steps of an approach run to the take-off board.
CM lowering	The amount of CM height lowered from take-off of last step to minimum CM height when in contact with the board.
Loss in horizontal velocity [*m/s*]	The change in horizontal velocity from touchdown (TD) on the board to take-off off the board.
Horizontal velocity at take-off [*m/s*]	The athlete's horizontal CM velocity at instant of take-off.
Vertical velocity at take-off [*m/s*]	The athlete's vertical direction of CM at instant of take-off.
Take-off angle (˚)	The angle of athlete's CM at instant of take-off on board relative to the horizontal.
Body inclination angle (at touchdown & take-off)	The angle between athlete's CM and contact foot relative to vertical position at touchdown and take-off from board.
Trunk angle at board (˚)	The trunk angle at take-off on board relative to 90˚ in an upright anatomical position.
Knee angle at board (˚)	The angle between thigh and shank (lower leg) at touchdown on the board relative to 180˚ in anatomical position.
Knee ROM	The change in knee angle at touchdown on the board to its minimum while taking off on board.
Flight technique	The type of flight technique used during the trajectory of the flight phase.

From the long jump variables listed above, a focus was made on horizontal jump variables and postural characteristics of a step cycle during the approach acceleration in preparation for take-off.

3.10 STATISTICAL ANALYSIS

Statistical analyses include mean and standard deviation values for all analyzed variables presented. Pearson's correlations were found between specific variables, times, and velocities. Effect size (Cohen's d) was calculated and interpreted as trivial (ES: $\leq$ 0.20, small ($0.21 \leq d < 0.60$), moderate ($0.61 \leq d < 1.20$), and large ($1.21 \leq d < 2.00$), and very large ($d > 2.01$) difference between the means of select kinematic variables (Cohen, 1988).

Chapter 4
RESULTS

4.1 INTRODUCTION

This chapter offers data on the live capture of the 2021 NCAA championship race rounds leading to the 100-m final and long jump final. Results from each round have been provided and include ranking, wind reading, official time or mark, season best, and personal best times and marks for each discipline.

4.2 SPRINT DISCIPLINE – 100-m

4.2.1 *SPRINT RACE RESULTS*

The following sections of results include data from the NCAA Women’s 100-m final.

A total of 96 collegiate finalists qualified for a chance to be in the final of the NCAA Women's 100-m. The West and East Regions each had 48 qualifiers compete in 6 heats in the First Round of the NCAA Championships. Each region held 3 heats to advance 24 competitors, totaling 48 sprinters, to the Quarterfinals (second round). From the Quarterfinals, 12 qualifiers out of 3 heats from each region advanced to Eugene, Oregon for the Semi-finals (third round) and the Final (fourth round). Advancement to compete in 1 of the 3 Semi-final heats was determined by the top 3 from each Quarterfinal heat plus the next 3 best times. Advancement to one heat of the Finals was determined by the top 2 from each Semi-final heat plus the next 3 best times.

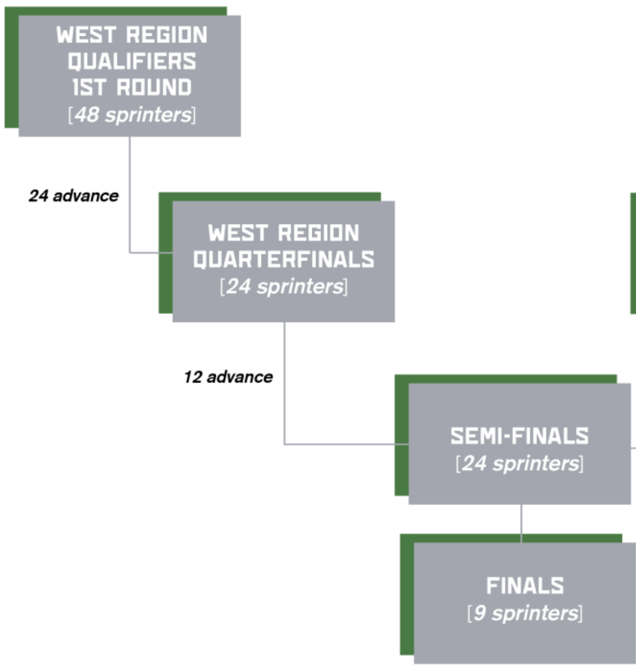


Figure 4.1. Advancement in the rounds of the NCAA Women's 100-m.

Results include the First Round, Quarterfinals, Semi-finals, and the Final of the Women's 100-m, with a more in-depth look at temporal and kinematic characteristics for each finalist within a calibrated volume during two specific stages of the race: the acceleration (13 – 20-m) and maximal velocity (40 – 47-m) phases. For record purposes, including meet, collegiate, and facility records, 'legal wind' races are denoted in green, and 'wind-aided' races are denoted in red.

Table 4.1. Abbreviations used for sprints.

DNS	Did not start	SB	Season's best time
DNF	Did not finish	PB	Personal best time

Table 4.2 below shows the official times of each athlete (48 competitors) in the 6 West Region NCAA First Round heats of the Women's 100-m alongside a comparison with their personal and season's bests. The mean sprint time of all competitors was 11.40 seconds; the mean difference compared with season's bests was 0.04 seconds; and the mean difference compared with personal bests was -0.09 seconds.

Athlete	Rank	Wind (m/s)	Official Time (s)	SB [2021] (s)	Compared to SB (s)	PB (s)	Compared to PB (s)
SPRINTER 1	128	+1.6	11.48	11.63	-0.15	11.63	0.00
SPRINTER 2	7	+1.6	11.11	11.10	0.01	11.04	0.06
SPRINTER 3	65	+1.6	11.56	11.45	0.11	11.73	-0.28
SPRINTER 4	101	+1.6	11.55	11.54	0.01	11.59	-0.05
SPRINTER 5	88	+1.6	11.35	11.35	0.00	11.35	0.00
SPRINTER 6	45	+1.6	11.48	11.36	0.12	11.61	-0.25
SPRINTER 7	34	+1.6	11.09	11.09	0.00	11.09	0.00
SPRINTER 8	57	+1.6	11.28	11.28	0.00	11.28	0.00
SPRINTER 9	113	+2.0	11.70	11.60	0.10	11.67	-0.07
SPRINTER 10	120	+2.0	11.61	11.62	-0.01	11.70	-0.08
SPRINTER 11	75	+2.0	11.58	11.47	0.11	11.54	-0.07
SPRINTER 12	12	+2.0	11.19	11.18	0.01	11.16	0.02
SPRINTER 13	52	+2.0	11.30	11.30	0.00	11.30	0.00
SPRINTER 14	15	+2.0	11.26	11.21	0.05	11.21	0.00
SPRINTER 15	50	+2.0	11.55	11.38	0.17	11.54	-0.16
SPRINTER 16	69	+2.0	11.63	11.47	0.16	11.89	-0.42
SPRINTER 17	62	+0.8	11.42	11.42	0.00	11.42	0.00
SPRINTER 18	60	+0.8	11.30	11.30	0.00	11.30	0.00
SPRINTER 19	94	+0.8	11.82	11.54	0.28	11.54	0.00
SPRINTER 20	2	+0.8	10.99	10.99	0.00	10.98	0.01

SPRINTER 21	41	+0.8	11.48	11.34	0.14	11.66	-0.32
SPRINTER 22	139	+0.8	11.57	11.65	-0.08	11.65	0.00
SPRINTER 23	37	+0.8	11.39	11.33	0.06	11.23	0.10
SPRINTER 24	88	+0.8	11.88	11.53	0.35	11.97	-0.44
SPRINTER 25	9	+2.7	11.08	11.08	0.00	11.12	-0.04
SPRINTER 26	82	+2.7	11.65	11.52	0.13	11.64	-0.12
SPRINTER 27	54	+2.7	11.48	11.4	0.08	11.40	0.00
SPRINTER 28	30	+2.7	11.22	11.22	0.00	11.29	-0.07
SPRINTER 29	120	+2.7	11.53	11.62	-0.09	11.90	-0.28
SPRINTER 30	47	+2.7	11.58	11.34	0.24	11.35	-0.01
SPRINTER 31	110	+2.7	11.38	11.38	0.00	11.47	-0.09
SPRINTER 32	65	+2.7	11.54	11.45	0.09	11.65	-0.20
SPRINTER 33	98	+2.1	11.44	11.56	-0.12	11.46	0.10
SPRINTER 34	36	+2.1	11.27	11.27	0.00	11.32	-0.05
SPRINTER 35	65	+2.1	11.42	11.45	-0.03	11.49	-0.04
SPRINTER 36	133	+2.1	11.57	11.64	-0.07	11.64	0.00
SPRINTER 37	60	+2.1	11.27	11.27	0.00	11.42	-0.15
SPRINTER 38	43	+2.1	11.37	11.35	0.02	11.35	0.00
SPRINTER 39	88	+2.1	11.36	11.36	0.00	11.80	-0.44
SPRINTER 40	5	+2.1	10.91	10.91	0.00	11.18	-0.27
SPRINTER 41	110	+2.8	11.12	11.12	0.00	11.20	-0.08
SPRINTER 42	120	+2.8	11.55	11.62	-0.07	11.73	-0.11
SPRINTER 43	11	+2.8	11.19	11.14	0.05	11.14	0.00
SPRINTER 44	69	+2.8	11.38	11.38	0.00	11.30	0.08
SPRINTER 45	26	+2.8	11.02	11.02	0.00	11.27	-0.25
SPRINTER 47	82	+2.8	11.65	11.52	0.13	11.52	0.00
SPRINTER 48	47	+2.8	11.20	11.20	0.00	11.37	-0.17

Table 4.2. Comparison of official race time, season best, and personal best from Women's 100-m First Round in the West Region. (*Note: Temperature, wind, humidity, pressure, and altitude were not recorded at this location.*)

Table 4.3 below shows the official times of each athlete (48 competitors) in the 6 East Region NCAA First Round heats of the Women's 100-m alongside a comparison with their personal and season's bests. The mean sprint time of all competitors was 11.48 seconds; the mean difference compared with season's bests was 0.11 seconds; and the mean difference compared with personal bests was -0.04 seconds.

Athlete	Rank	Wind (m/s)	Official Time (s)	SB [2021] (s)	Compared to SB (s)	PB (s)	Compared to PB (s)
SPRINTER 1	98	+1.9	11.47	11.56	-0.09	11.59	-0.03
SPRINTER 2	4	+1.9	11.01	11.03	-0.02	11.17	-0.14
SPRINTER 3	19	+1.9	11.29	11.23	0.06	11.31	-0.08
SPRINTER 4	69	+1.9	11.39	11.47	-0.08	11.47	0.00
SPRINTER 5	41	+1.9	11.41	11.34	0.07	11.24	0.10
SPRINTER 6	28	+1.9	11.42	11.28	0.14	11.22	0.06
SPRINTER 7	82	+1.9	11.73	11.52	0.21	11.54	-0.02
SPRINTER 8	116	+1.9	11.52	11.61	-0.09	11.75	-0.14
SPRINTER 9	120	+1.6	11.63	11.62	0.01	11.87	-0.25
SPRINTER 10	22	+1.6	11.29	11.26	0.03	11.29	-0.03
SPRINTER 11	52	+1.6	11.62	11.39	0.23	11.57	-0.18
SPRINTER 12	22	+1.6	11.22	11.26	-0.04	11.26	0.00
SPRINTER 13	88	+1.6	11.51	11.53	-0.02	11.53	0.00
SPRINTER 14	1	+1.6	11.31	10.87	0.44	10.96	-0.09
SPRINTER 15	88	+1.6	11.55	11.53	0.02	11.53	0.00
SPRINTER 16	57	+1.6	11.50	11.41	0.09	11.65	-0.24
SPRINTER 17	101	+1.4	11.98	11.57	0.41	11.74	-0.17
SPRINTER 18	79	+1.4	11.79	11.51	0.28	11.51	0.00
SPRINTER 19	37	+1.4	11.23	11.33	-0.10	11.11	0.22
SPRINTER 20	75	+1.4	11.63	11.50	0.13	11.50	0.00

SPRINTER 21	30	+1.4	11.38	11.29	0.09	11.04	0.25
SPRINTER 22	7	+1.4	11.18	11.10	0.08	11.25	-0.15
SPRINTER 23	105	+1.4	11.64	11.58	0.06	11.88	-0.30
SPRINTER 24	17	+1.4	11.25	11.22	0.03	11.22	0.00
SPRINTER 25	105	+1.2	11.66	11.58	0.08	11.63	-0.05
SPRINTER 26	79	+1.2	11.55	11.51	0.04	11.51	0.00
SPRINTER 27	105	+1.2	11.69	11.58	0.11	11.79	-0.21
SPRINTER 28	30	+1.2	11.37	11.29	0.08	11.16	0.13
SPRINTER 29	75	+1.2	11.53	11.50	0.03	11.55	-0.05
SPRINTER 30	9	+1.2	11.17	11.12	0.05	11.12	0.00
SPRINTER 31	13	+1.2	11.50	11.19	0.31	11.19	0.00
SPRINTER 32	33	+1.2	11.45	11.30	0.15	11.30	0.00
SPRINTER 33	101	+2.2	11.70	11.57	0.13	11.44	0.13
SPRINTER 34	28	+2.2	11.48	11.28	0.20	11.28	0.00
SPRINTER 35	5	+2.2	11.15	11.08	0.07	11.23	-0.15
SPRINTER 36	116	+2.2	11.60	11.61	-0.01	11.41	0.20
SPRINTER 37	72	+2.2	11.52	11.48	0.04	11.53	-0.05
SPRINTER 38	17	+2.2	11.28	11.22	0.06	11.28	-0.06
SPRINTER 39	82	+2.2	11.51	11.52	-0.01	11.57	-0.05
SPRINTER 40	37	+2.2	11.55	11.33	0.22	11.33	0.00
SPRINTER 41	50	+0.9	11.55	11.38	0.17	11.44	-0.06
SPRINTER 42	19	+0.9	11.62	11.23	0.39	11.23	0.00
SPRINTER 43	68	+0.9	11.37	11.46	-0.09	11.46	0.00
SPRINTER 44	94	+0.9	11.85	11.54	0.31	11.54	0.00
SPRINTER 45	2	+0.9	11.23	11.02	0.21	11.02	0.00
SPRINTER 47	82	+0.9	11.79	11.52	0.27	11.52	0.00
SPRINTER 48	22	+0.9	11.45	11.26	0.19	11.32	-0.06

Table 4.3. Comparison of official race time, season best, and personal best from Women's 100-m First Round in the East Region. (*Note: 78°F, wind 2 mph SE, humidity 78%, pressure 29.66in, and altitude 46ft (race conditions adapted from flashresults.com)*)

Table 4.4 below shows the official times of each athlete (24 competitors) in the 3 West Region NCAA Quarterfinal heats of the Women's 100-m alongside a comparison with their personal and season's bests. The mean sprint time of all competitors was 11.39 seconds; the mean difference compared with season's bests was 0.18 seconds; and the mean difference compared with personal bests was -0.06 seconds.

Athlete	Rank	Wind (m/s)	Official Time (s)	SB [2021] (s)	Compared to SB (s)	PB (s)	Compared to PB (s)
SPRINTER 1	88	+0.6	11.72	11.36	0.36	11.80	-0.44
SPRINTER 2	57	+0.6	11.57	11.28	0.29	11.28	0.00
SPRINTER 3	30	+0.6	11.39	11.22	0.17	11.29	-0.07
SPRINTER 4	26	+0.6	11.29	11.02	0.27	11.27	-0.25
SPRINTER 5	9	+0.6	11.27	11.08	0.19	11.12	-0.04
SPRINTER 6	15	+0.6	11.45	11.21	0.24	11.21	0.00
SPRINTER 7	52	+0.6	11.53	11.30	0.23	11.30	0.00
SPRINTER 8	43	+0.6	11.48	11.35	0.13	11.35	0.00
SPRINTER 9	47	+0.1	11.48	11.20	0.28	11.37	-0.17
SPRINTER 10	11	+0.1	11.44	11.14	0.30	11.14	0.00
SPRINTER 11	7	+0.1	11.27	11.10	0.17	11.04	0.06
SPRINTER 12	5	+0.1	10.98	10.91	0.07	11.18	-0.27
SPRINTER 13	12	+0.1	11.34	11.18	0.16	11.16	0.02
SPRINTER 14	60	+0.1	11.87	11.30	0.57	11.30	0.00
SPRINTER 15	37	+0.1	11.41	11.33	0.08	11.23	0.10
SPRINTER 16	62	+0.1	DNS	11.42	-	11.42	0.00
SPRINTER 17	88	+1.3	11.52	11.35	0.17	11.35	0.00
SPRINTER 18	36	+1.3	11.37	11.27	0.10	11.32	-0.05
SPRINTER 19	110	+1.3	11.27	11.12	0.15	11.20	-0.08
SPRINTER 20	2	+1.3	10.89	10.99	-0.10	10.98	0.01

SPRINTER 21	34	+1.3	11.15	11.09	0.06	11.09	0.00
SPRINTER 22	60	+1.3	11.40	11.27	0.13	11.42	-0.15
SPRINTER 23	110	+1.3	11.47	11.38	0.09	11.47	-0.09
SPRINTER 24	69	+1.3	11.52	11.38	0.14	11.30	0.08

Table 4.4. Comparison of official race time, season best, and personal best from Women's 100-m quarterfinalists in the West Region. (*Note: DNS = did not start; 76°F, wind 0 mph WSW, humidity 49%, pressure 29.62in, and altitude 331ft (race conditions adapted from flashresults.com)*)

Table 4.5 below shows the official times of each athlete (24 competitors) in the 3 East Region NCAA Quarterfinal heats of the Women's 100-m alongside a comparison with their personal and season's bests. The mean sprint time of all competitors was 11.29 seconds; mean difference compared with season's bests was 0.06 seconds; and mean difference compared with personal bests was 0.01 seconds.

Athlete	Rank	Wind (m/s)	Official Time (s)	SB [2021] (s)	Compared to SB (s)	PB (s)	Compared to PB (s)
SPRINTER 1	28	-0.8	11.38	11.28	0.10	11.22	0.06
SPRINTER 2	69	-0.8	11.40	11.39	0.01	11.39	0.00
SPRINTER 3	22	-0.8	11.44	11.26	0.18	11.29	-0.03
SPRINTER 4	9	-0.8	11.17	11.12	0.05	11.12	0.00
SPRINTER 5	7	-0.8	11.21	11.18	0.03	11.18	0.00
SPRINTER 6	19	-0.8	11.48	11.29	0.19	11.29	0.00
SPRINTER 7	22	-0.8	11.31	11.26	0.05	11.32	-0.06
SPRINTER 8	98	-0.8	11.54	11.47	0.07	11.47	0.00
SPRINTER 9	41	0.0	11.28	11.34	-0.06	11.24	0.10

SPRINTER 10	1	0.0	10.98	10.87	0.11	10.96	-0.09
SPRINTER 11	17	0.0	11.26	11.22	0.04	11.28	-0.06
SPRINTER 12	5	0.0	11.12	11.08	0.04	11.23	-0.15
SPRINTER 13	22	0.0	11.15	11.22	-0.07	11.22	0.00
SPRINTER 14	68	0.0	11.38	11.37	0.01	11.37	0.00
SPRINTER 15	33	0.0	11.44	11.3	0.14	11.30	0.00
SPRINTER 16	57	0.0	11.68	11.41	0.27	11.50	-0.09
SPRINTER 17	30	+1.4	11.44	11.29	0.15	11.04	0.25
SPRINTER 18	17	+1.4	11.22	11.22	0.00	11.22	0.00
SPRINTER 19	37	+1.4	11.33	11.23	0.10	11.11	0.12
SPRINTER 20	4	+1.4	10.92	11.01	-0.09	11.01	0.00
SPRINTER 21	2	+1.4	11.03	11.02	0.01	11.02	0.00
SPRINTER 22	30	+1.4	11.25	11.29	-0.04	11.16	0.13
SPRINTER 23	28	+1.4	11.36	11.28	0.08	11.28	0.00
SPRINTER 24	13	+1.4	11.27	11.19	0.08	11.19	0.00

Table 4.5. Comparison of official race time, season best, and personal best from Women's 100-m quarterfinalists in the East Region. *(Note: 82°F, wind 1 mph NW, humidity 66%, pressure 30.09in, and altitude 49ft (race conditions adapted from flashresults.com)*)

Table 4.6 below shows the official times of each athlete (24 competitors) in the 3 Semi-final NCAA heats of the Women's 100-m alongside a comparison with their personal and season's bests. The mean sprint time of all competitors was 11.41 seconds; the mean difference compared with season's bests was 0.28 seconds; and the mean difference compared with personal bests was -0.03 seconds.

Athlete	Rank	Wind (m/s)	Official Time (s)	SB [2021] (s)	Compared to SB (s)	PB (s)	Compared to PB (s)
SPRINTER 1	33	+0.5	11.40	11.27	0.13	11.32	-0.05
SPRINTER 2	30	+0.5	11.43	11.26	0.17	11.31	-0.05
SPRINTER 3	5	+0.5	11.39	11.02	0.37	11.02	0.00
SPRINTER 4	1	+0.5	11.16	10.87	0.29	10.96	-0.09
SPRINTER 5	2	+0.5	11.03	10.89	0.14	10.89	0.00
SPRINTER 6	9	+0.5	11.39	11.09	0.30	11.09	0.00
SPRINTER 7	22	+0.5	11.43	11.22	0.21	11.22	0.00
SPRINTER 8	28	+0.5	11.39	11.25	0.14	11.16	0.09
SPRINTER 9	45	-0.9	11.60	11.33	0.27	11.23	0.10
SPRINTER 10	12	-0.9	11.49	11.12	0.37	11.20	-0.08
SPRINTER 11	10	-0.9	11.47	11.10	0.37	11.04	0.06
SPRINTER 12	12	-0.9	11.30	11.12	0.18	11.12	0.00
SPRINTER 13	7	-	DNS	11.08	-	11.12	-0.04
SPRINTER 14	7	-0.9	11.46	11.08	0.38	11.12	-0.04
SPRINTER 15	15	-0.9	11.40	11.15	0.25	11.15	0.00
SPRINTER 16	17	-0.9	11.68	11.19	0.49	11.19	0.00
SPRINTER 17	33	-0.5	11.67	11.27	0.40	11.40	-0.13
SPRINTER 18	22	-0.5	11.65	11.22	0.43	11.29	-0.07
SPRINTER 19	5	-0.5	11.46	11.02	0.44	11.27	-0.25
SPRINTER 20	3	-0.5	11.13	10.91	0.22	10.98	-0.07
SPRINTER 21	4	-0.5	11.20	10.92	0.28	10.92	0.00
SPRINTER 22	10	-0.5	11.43	11.10	0.33	11.18	-0.08
SPRINTER 23	16	-0.5	11.35	11.18	0.17	11.16	0.02
SPRINTER 24	22	-0.5	11.57	11.22	0.35	11.26	-0.04

Table 4.6. Comparison of official race time, season best, and personal best from Women's 100-m semi-finalists. (*Note:* 67°*F, wind 0 mph W, humidity 45%, pressure 30.09in, and altitude 470ft (race conditions adapted from flashresults.com)*)

4.2.2 *SPRINT FINALISTS*

The following section of results includes data from the nine 100-m finalists, derived from key temporal and kinematic data at specific stages of the race.

Figure 4.2 and Table 4.7 below present the progression of times posted by each finalist in each round taken to reach the 100-m final (chart and table format). Times for each round are given in seconds (s).

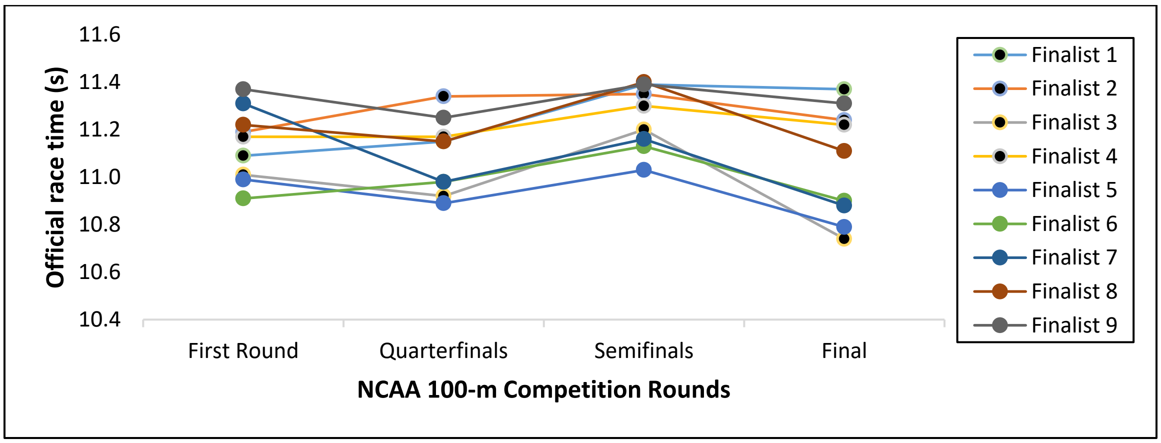


Figure 4.2. Figure presentation of times posted in each round leading into the final by each female 100-m finalist.

Table 4.7 shows mean ± SD for the First Round, Quarterfinals, Semi-finals, and Final was 11.14 ± 0.24 s, 11.09 ± 0.16 s, 11.27 ± 0.12 s, and 11.06 ± 0.24 s, respectively.

Athlete	First Round (s)	Quarterfinals (s)	Semi-finals (s)	Final (s)
FINALIST 1	11.09	11.15	11.39	11.37
FINALIST 2	11.19	11.34	11.35	11.24
FINALIST 3	11.01	10.92	11.20	10.74
FINALIST 4	11.17	11.17	11.30	11.22
FINALIST 5	10.99	10.89	11.09	10.79
FINALIST 6	10.91	10.98	11.13	10.90
FINALIST 7	11.31	10.98	11.16	10.88
FINALIST 8	11.22	11.15	11.40	11.11
FINALIST 9	11.37	11.25	11.39	11.31
MEAN ± SD	11.14 ± 0.24	11.09 ± 0.16	11.27 ± 0.12	11.06 ± 0.24

Table 4.7. Table presentation of times posted in each round leading into the final by each female 100-m finalist.

Having provided the performance trends seen in the first round, quarterfinals, and semi-finals, the table below shows the official times of each athlete (9 competitors) in the Final of the Women's 100-m alongside a comparison with their personal and season's bests.

Table 4.8 shows the mean sprint time of all competitors was 11.06 seconds; the mean difference compared with season's bests was 0.02 seconds; and the mean difference compared with personal bests was -0.01 seconds.

Athlete	Rank	Wind (m/s)	Official Time (s)	SB [2021] (s)	Compared to SB (s)	PB (s)	Compared to PB (s)
FINALIST 1	9	+2.2	11.37	11.09	0.28	11.09	0.00
FINALIST 2	16	+2.2	11.24	11.18	0.06	11.16	0.02
FINALIST 3	4	+2.2	10.74	10.92	-0.18	10.92	0.00
FINALIST 4	12	+2.2	11.22	11.12	0.10	11.12	0.00
FINALIST 5	2	+2.2	10.79	10.89	-0.10	10.89	0.00
FINALIST 6	3	+2.2	10.90	10.91	-0.01	10.98	-0.07
FINALIST 7	1	+2.2	10.88	10.87	0.01	10.96	-0.09
FINALIST 8	15	+2.2	11.11	11.15	-0.04	11.15	0.00
FINALIST 9	28	+2.2	11.31	11.25	0.06	11.16	0.09
MEAN ± SD			11.06 ± 0.24	11.04 ± 0.14		11.05 ± 0.11	

Table 4.8. Comparison of official race time, season best, and personal best from Women 100-m finalists. (*Note: Negative (-) sign indicates a decrease (improvement) in time by seconds; 78°F, wind 0 mph NE, humidity 52%, pressure 29.80in, and altitude 470ft* (*adapted from flashresults.com*)).

Table 4.9 below shows the final race time of the Women's 100-m along with the number of steps taken in the race by the finalists. The mean ± SD the official race time was 11.06 ± 0.24 while mean ± SD for steps taken was 49.6 ± 1.67.

Athlete	Official Time (s)	Number of Steps (#)
FINALIST 1	11.37	49
FINALIST 2	11.24	46
FINALIST 3	10.74	49
FINALIST 4	11.22	51
FINALIST 5	10.79	50
FINALIST 6	10.90	50
FINALIST 7	10.88	50
FINALIST 8	11.11	49
FINALIST 9	11.31	52
MEAN ± SD	11.06 ± 0.24	49.6 ± 1.67

Table 4.9. Final race time and number of steps taken in the race by the nine 100-m Women finalists.

Table 4.10 below shows the reaction times of each finalist in the Women's 100-m in comparison to their reaction time in the semi-finals. The mean ± SD difference between the semi-final and final was -0.006 ± 0.02 s.

Athlete	Semi-finals RT (s)	Finals RT (s)	Difference (s)
FINALIST 1	0.167	0.137	-0.030
FINALIST 2	0.133	0.146	+0.013
FINALIST 3	0.150	0.124	-0.026
FINALIST 4	0.230	0.187	-0.043
FINALIST 5	0.154	0.180	+0.026
FINALIST 6	0.176	0.185	+0.009
FINALIST 7	0.176	0.193	+0.017
FINALIST 8	0.213	0.200	-0.013
FINALIST 9	0.145	0.141	-0.004
MEAN ± SD	0.172 ± 0.03	0.166 ± 0.03	-0.006 ± 0.02

Table 4.10. Reaction times (RT) in the third (Semi-finals) and fourth (Finals) rounds. (*Note: Negative (-) sign indicates a decrease (improvement) in time, while plus (+) sign indicates an increase (slower) in time by seconds.*)

Table 4.11 below shows the reaction times of each finalist in the Women's 100-m and the ranking of these times at the start of the race, and in comparison, to final race results. The correlation between reaction time and final performance results was r = -0.22.

Athlete	RT (s)	Ranking of RT	Final Race Finish
FINALIST 1	0.137	2	9
FINALIST 2	0.146	4	7
FINALIST 3	0.124	1	1
FINALIST 4	0.187	7	6
FINALIST 5	0.180	5	2
FINALIST 6	0.185	6	4
FINALIST 7	0.193	8	3
FINALIST 8	0.200	9	5
FINALIST 9	0.141	3	8
MEAN ± SD	0.166 ± 0.03		

Table 4.11. Reaction times (RT), ranking of reaction times, and race finish of finalist in the Women’s 100-m final.

Table 4.12 below shows a comparison of overall race velocity achieved between the last two rounds (Semi-finals and Finals) achieved by the finalist in the Women's 100-m. Velocity is given in m/s. A mean sprint time of 8.89 m/s was reached in the Semi-finals whereas a mean sprint time of 9.04 m/s was reached in the Finals. Finalists increased velocity with a mean of +2%.

Athlete	Semi-finals 0-100 m (m/s)	Finals 0-100 m (m/s)	Difference %
FINALIST 1	8.78	8.80	+0.17
FINALIST 2	8.87	8.90	+0.34
FINALIST 3	8.93	9.31	+4.26
FINALIST 4	8.85	8.91	+0.68
FINALIST 5	9.07	9.27	+2.21
FINALIST 6	8.98	9.17	+2.12
FINALIST 7	8.96	9.19	+2.57
FINALIST 8	8.77	9.00	+2.62
FINALIST 9	8.78	8.84	+0.68
MEAN ± SD	8.89 ± 0.10	9.04 ± 0.19	2% ± 0.01

Table 4.12. Race velocity difference in percent between the Semi-Final and Final in velocity by the 9 female finalists. (*Note: Plus (+) sign indicates the increase in the percentage of rate of speed by m/s.*)

Table 4.13 below is an evaluation of phases by velocity achieved among the finalists in the Women's 100-m final. Sprint velocity of each phase is given in m/s. Mean ± SD was 7.37 ± 0.10 m/s (0 – 30 m), 10.34 ± 0.23 m/s (30 – 60 m/s), 9.79 ± 0.33 m/s (60 – 100 m), and 9.04 ± 0.19 m/s (0 – 100 m).

Athlete	0-30 m (m/s)	30-60 m (m/s)	60-100 m (m/s)	0-100 m (m/s)
FINALIST 1	7.28	10.10	9.34	8.80
FINALIST 2	7.30	10.05	9.65	8.90
FINALIST 3	7.49	10.58	10.21	9.31
FINALIST 4	7.36	10.40	9.42	8.91
FINALIST 5	7.43	10.71	10.12	9.27
FINALIST 6	7.49	10.46	9.93	9.17
FINALIST 7	7.45	10.40	10.07	9.19
FINALIST 8	7.25	10.28	9.87	9.00
FINALIST 9	7.28	10.10	9.48	8.84
MEAN ± SD	7.37 ± 0.10	10.34 ± 0.23	9.79 ± 0.33	9.04 ± 0.19

Table 4.13. Velocity reached during acceleration (0-30), maximal velocity (30-60), maintenance and deceleration (60-100) and the full race (0-100) by the 9 female finalists.

Table 4.14 below is an evaluation of speed times reached in each phase of the 100-m (acceleration phase, maximal velocity phase, deceleration phase) among the finalists during the Women's 100-m given in seconds. Mean ± SD was 4.07 ± 0.06 m/s (0 – 30 m), 2.90 ± 0.06 m/s (30 – 60 m/s), and 4.09 ± 0.14 m/s (60 – 100 m).

Athlete	0-30 m (s)	30-60 m (s)	60-100 m (s)
FINALIST 1	4.12	2.97	4.28
FINALIST 2	4.11	2.99	4.14
FINALIST 3	4.00	2.84	3.92
FINALIST 4	4.08	2.89	4.25
FINALIST 5	4.04	2.80	3.95
FINALIST 6	4.00	2.87	4.03
FINALIST 7	4.03	2.89	3.97
FINALIST 8	4.14	2.92	4.05
FINALIST 9	4.12	2.97	4.22
MEAN ± SD	4.07 ± 0.06	2.90 ± 0.06	4.09 ± 0.14

Table 4.14. Velocity reached during acceleration (0-30), maximal velocity (30-60), and the maintenance and deceleration (60-100) by the 9 female finalists.

4.2.2.1 *Acceleration Phase*

The following section of results includes data from the Women's 100-m final derived from key temporal and kinematic data during a selected calibrated volume of the race (13 – 20-m) in the acceleration phase.

Table 4.15 below displays the mean step length, step rate, and step width of each finalist in the entire acceleration phase as the average of acceleration sub-phases 1 and 2. The mean ± SD was 1.92 ± 0.06 m, 4.83 ± 0.22 Hz, 0.15 ± 0.07 m, respectively.

Athlete	Step length (m)	Step rate (Hz)	Step width (m)
FINALIST 1	1.96	4.58	0.26
FINALIST 2	2.03	4.44	0.08
FINALIST 3	1.95	4.82	0.21
FINALIST 4	1.82	5.07	0.11
FINALIST 5	1.93	4.99	0.17
FINALIST 6	1.92	5.00	0.11
FINALIST 7	1.90	4.94	0.21
FINALIST 8	1.92	4.69	0.16
FINALIST 9	1.84	4.94	0.07
MEAN ± SD	1.92 ± 0.06	4.83 ± 0.22	0.15 ± 0.07

Table 4.15. Mean step length, step rate, and step width across and up to four steps during the entire acceleration phase for each female finalist.

Figure 4.3 below displays the mean contact time, flight time, and step time of all finalists in the entire acceleration phase as the average of acceleration sub-phases 1 and 2. The mean ± SD was 0.10 ± 0.01 s.

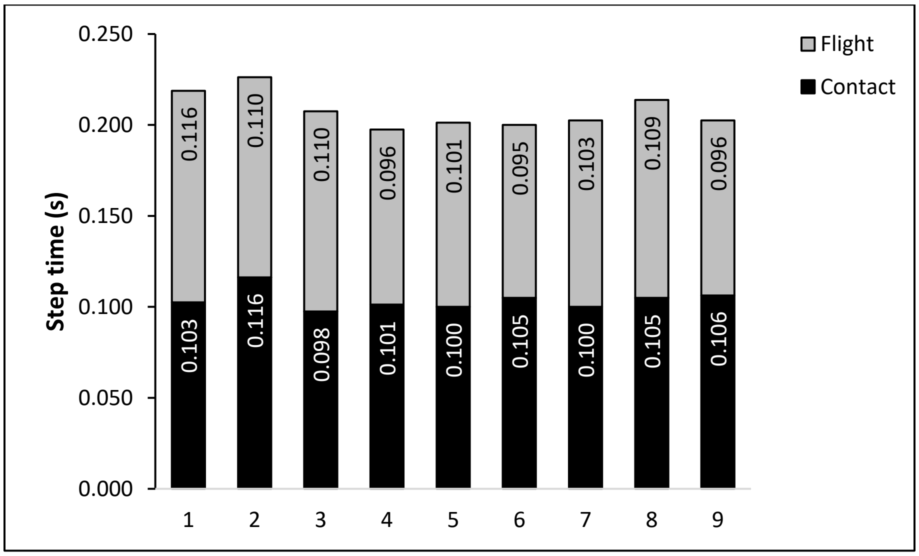


Figure 4.3. Mean contact, flight, and step time during acceleration for each female finalist. Step time is the sum of contact and flight times.

The following data covers specific velocity variables during the acceleration phase for all finalists. Notable changes in step pattern may have occurred for finalists 4, 5, 6, 7, and 9.

Table 4.16 below displays the mean step velocity and CM horizontal velocity of each finalist in the entire acceleration phase as the average of acceleration sub-phases 1 and 2. The mean ± SD was 9.24 ± 0.33 m/s and 9.00 ± 0.30 m/s, respectively.

Athlete	Step velocity (m/s)	CM horizontal velocity (m/s)
FINALIST 1	8.73	8.64
FINALIST 2	9.02	8.97
FINALIST 3	9.40	9.22
FINALIST 4	9.33	8.47
FINALIST 5	9.77	9.30
FINALIST 6	9.60	9.33
FINALIST 7	9.27	9.09
FINALIST 8	8.93	9.12
FINALIST 9	9.11	8.85
MEAN ± SD	9.24 ± 0.33	9.00 ± 0.30

Table 4.16. Mean running velocity across and up to four steps for each female finalist. (*Note: Step velocity was calculated using step length and step time*, *whereas the CM velocity was calculated from the full-body digitized data*.)

Figure 4.4 below displays the mean CM horizontal velocities of the right-to-left leg and left-to-right leg of all finalists in the acceleration phase as the average of acceleration sub-phases 1 and 2. The mean ± SD for the left-right steps was 9.04 ± 0.25 m/s and 8.95 ± 0.50 m/s for the right-left steps.

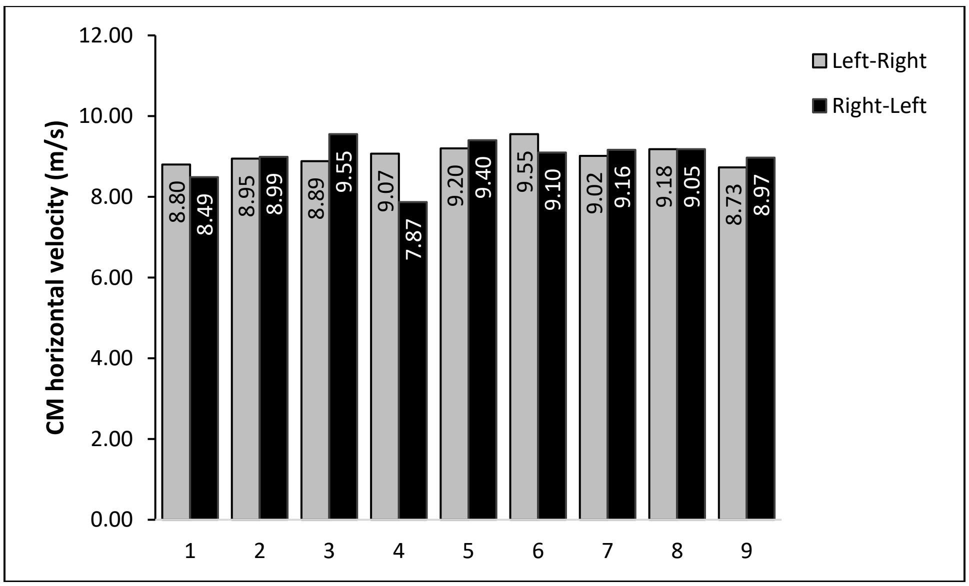


Figure 4.4. Individual mean center of mass (CM) horizontal velocities for the right-left and left-right digitized steps for each female finalist.

Figure 4.5 below displays the mean swing time of all finalists in the acceleration phase as the average of acceleration sub-phases 1 and 2. The mean ± SD was 0.311 ± 0.02 s.

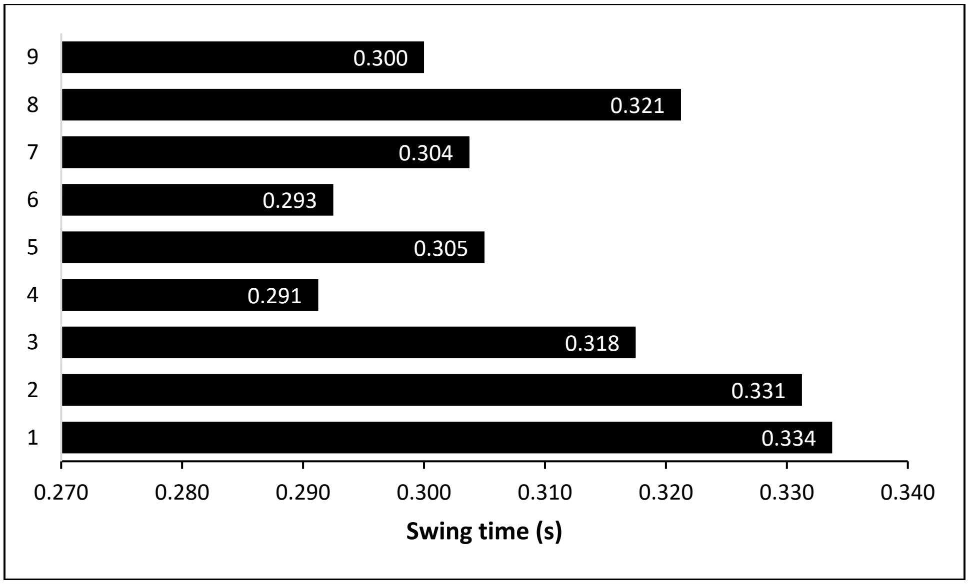


Figure 4.5. Mean swing time of one stride for each athlete. For some athletes, the stride was left-left contact for some and right-right contact for others.

Table 4.17 below displays the mean horizontal distance at touchdown and toe-off of each finalist in the entire acceleration phase as the average of acceleration sub-phases 1 and 2. The mean ± SD was 0.25 ± 0.04 m (DCM TD left), 0.28 ± 0.04 m (DCM TD right), 0.67 ± 0.04 m (DCM TO left), and 0.68 ± 0.04 m (DCM TO right).

	DCM TD (m)		DCM TO (m)	
Athlete	**Left**	**Right**	**Left**	**Right**
FINALIST 1	0.28	0.22	0.63	0.62
FINALIST 2	0.27	0.33	0.67	0.67
FINALIST 3	0.28	0.28	0.63	0.62
FINALIST 4	0.28	0.26	0.65	0.69
FINALIST 5	0.20	0.32	0.70	0.71
FINALIST 6	0.29	0.26	0.70	0.74
FINALIST 7	0.19	0.26	0.67	0.68
FINALIST 8	0.23	0.33	0.75	0.73
FINALIST 9	0.27	0.28	0.66	0.70
MEAN ± SD	0.25 ± 0.04	0.28 ± 0.04	0.67 ± 0.04	0.68 ± 0.04

Table 4.17. Mean horizontal distance from the point of ground contact to the body's CM at both touchdown (DCM TD) and toe-off (DCM TO). (*Note: Data displayed as absolute distance.*)

Table 4.18 below displays the mean horizontal distance at touchdown and toe-off of each finalist in the acceleration phase as the average of acceleration sub-phases 1 and 2. The mean ± SD for DCM TD (left and right) was 0.27 ± 0.02 m and 0.68 ± 0.04 m for DCM TO (left and right).

Athlete	DCM TD (m)	DCM TO (m)
FINALIST 1	0.25	0.63
FINALIST 2	0.30	0.67
FINALIST 3	0.28	0.62
FINALIST 4	0.27	0.67
FINALIST 5	0.26	0.70
FINALIST 6	0.27	0.72
FINALIST 7	0.23	0.67
FINALIST 8	0.28	0.74
FINALIST 9	0.27	0.68
MEAN ± SD	0.27 ± 0.04	0.68 ± 0.04

Table 4.18. Mean horizontal distance from the point of ground contact to the body's CM at both touchdown (DCM TD) and toe-off (DCM TO). (*Note: Data displayed as absolute distance.*)

4.2.2.1.1 *Acceleration Phase – Sub-Phases 1 and 2*

The acceleration phase (13 – 20-m) was further divided into two sub-phases (first sub-phase, 13 – 16.5-m; second sub-phase, 16.5 – 20-m). The results of the first and second sub-acceleration phases have been provided below.

Table 4.19 below displays the step length, step rate, and step width of each finalist in the first sub-acceleration phase. The mean ± SD for the first sub-phase was 1.90 ± 0.06 m, 4.82 ± 0.21 Hz, 0.15 ± 0.06 m, respectively.

Athlete	Step length (m)	Step rate (Hz)	Step width (m)
FINALIST 1	1.94	4.60	0.24
FINALIST 2	2.00	4.42	0.09
FINALIST 3	1.94	4.82	0.19
FINALIST 4	1.81	5.01	0.08
FINALIST 5	1.91	4.91	0.18
FINALIST 6	1.92	5.00	0.14
FINALIST 7	1.87	5.01	0.20
FINALIST 8	1.94	4.72	0.10
FINALIST 9	1.82	4.95	0.10
MEAN ± SD	1.90 ± 0.06	4.82 ± 0.21	0.15 ± 0.06

Table 4.19. Step length, step rate, and step width across up to two steps during the first sub-acceleration phase for each female finalist.

Table 4.20 below displays the step length, step rate, and step width of each finalist in the second sub-acceleration phase. The mean ± SD for the second sub-phase was 1.93 ± 0.06 m, 4.83 ± 0.23 Hz, 0.16 ± 0.08 m, respectively.

Athlete	Step length (m)	Step rate (Hz)	Step width (m)
FINALIST 1	1.96	4.56	0.29
FINALIST 2	1.94	4.45	0.06
FINALIST 3	1.92	4.82	0.22
FINALIST 4	1.93	5.13	0.13
FINALIST 5	1.90	5.07	0.16
FINALIST 6	1.84	5.01	0.08
FINALIST 7	2.06	4.88	0.21
FINALIST 8	1.87	4.66	0.22
FINALIST 9	1.97	4.94	0.04
MEAN ± SD	1.93 ± 0.06	4.83 ± 0.23	0.16 ± 0.08

Table 4.20. Step length, step rate, and step width across up to two steps during the second sub-acceleration phase for each female finalist.

Figure 4.6 below displays the relationship between the step length and step rate of all finalists in the first sub-acceleration phase. The mean ± SD of this relationship for the first sub-phase was 9.16 ± 0.25 $m \cdot s^{-1}$ based on a multiple of SL and SR (SL x SR).

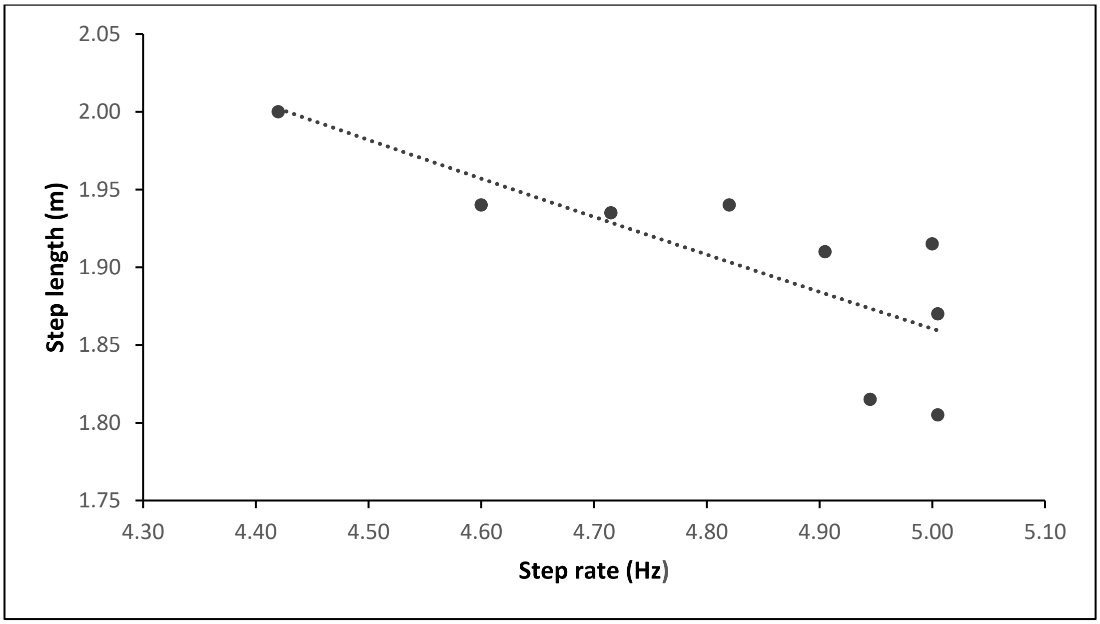


Figure 4.6. Scatterplot of the relationship between step rate and step length for up to two steps during the <u>first</u> sub-acceleration phase for each female finalist.

Figure 4.7 below displays the relationship between the step length and step rate of all finalists in the second sub-acceleration phase. The mean ± SD of this relationship for the second sub-phase was 9.38 ± 0.25 $m \cdot s^{-1}$ based on a multiple of SL and SR (SL x SR).

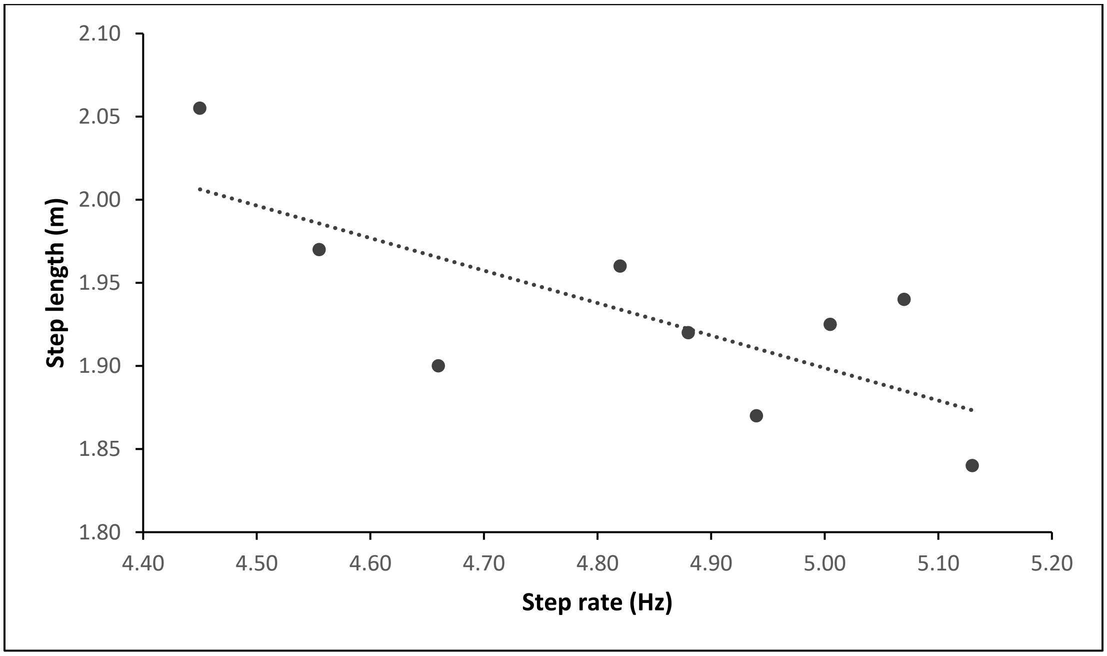


Figure 4.7. Scatterplot of the relationship between step rate and step length for up to two steps during the <u>second</u> sub-acceleration phase for each female finalist.

Figure 4.8 below displays the contact time, flight time, and step time of all finalists in the first sub-acceleration phase. The mean ± SD for the first sub-phase was 0.11 ± 0.01 s, 0.10 ± 0.01 s, 0.21 ± 0.01 s, respectively.

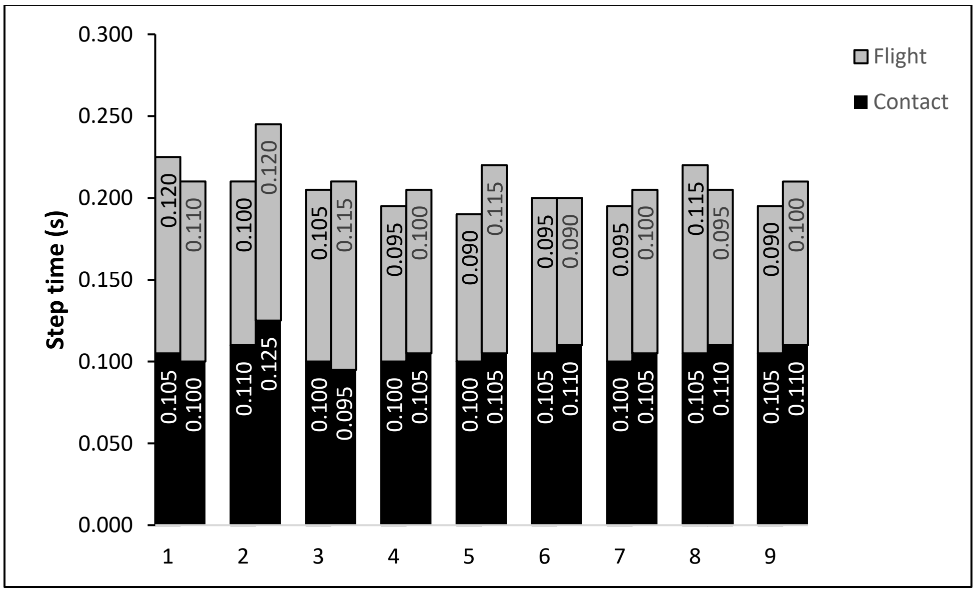


Figure 4.8. Contact, flight, and step time during the <u>first</u> sub-acceleration phase for each female finalist. Step time is the sum of contact and flight times. The left and right columns indicate the left and right legs of each athlete, respectively.

Figure 4.9 below displays the contact time, flight time, and step time of all finalists in the second sub-acceleration phase. The mean ± SD for the second sub-phase was 0.10 ± 0.01 s, 0.11 ± 0.01 s, 0.21 ± 0.01 s, respectively.

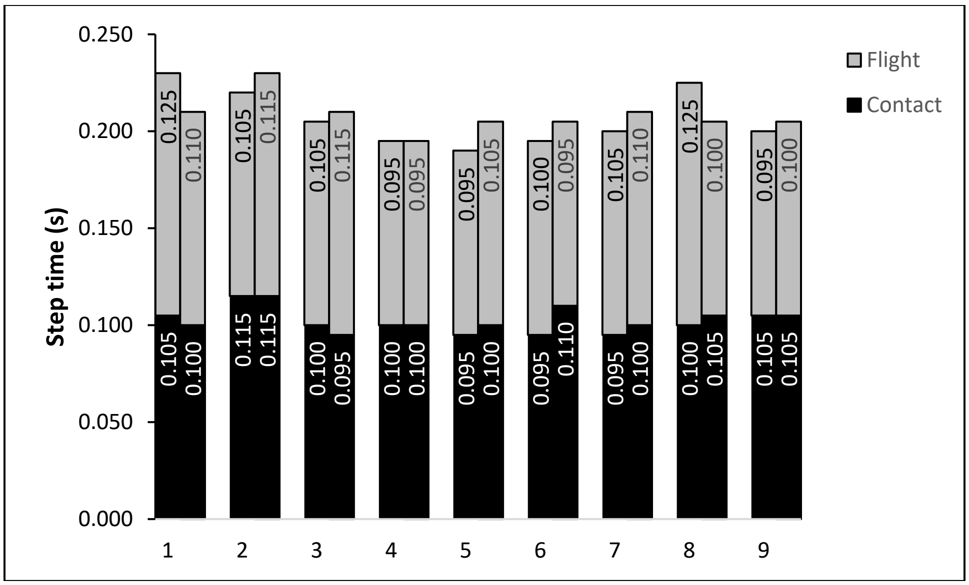


Figure 4.9. Contact, flight, and step time during the <u>second</u> sub-acceleration phase for each female finalist. Step time is the sum of contact and flight times. The left and right columns indicate the left and right legs of each athlete, respectively.

Table 4.21 below displays the step velocity and CM horizontal velocity of each finalist in the first sub-acceleration phase. The mean ± SD for the first sub-phase was 9.16 ± 0.26 m/s and 8.75 ± 0.44 m/s.

Athlete	Step velocity (m/s)	CM horizontal velocity (m/s)
FINALIST 1	8.90	8.54
FINALIST 2	8.77	8.72
FINALIST 3	9.33	9.00
FINALIST 4	9.05	7.68
FINALIST 5	9.32	9.13
FINALIST 6	9.60	9.04
FINALIST 7	9.35	8.86
FINALIST 8	9.11	9.04
FINALIST 9	8.97	8.77
MEAN ± SD	9.16 ± 0.26	8.75 ± 0.44

Table 4.21. Running velocity across up to two steps during the first sub-acceleration phase for each female finalist. (*Note: Step velocity was calculated using step length and step time, whereas the CM velocity was calculated from the full-body digitized data.*)

Table 4.22 below displays the step velocity and CM horizontal velocity of each finalist in the second sub-acceleration phase. The mean ± SD for the second sub-phase was 9.32 ± 0.31 m/s and 9.24 ± 0.28 m/s.

Athlete	Step velocity (m/s)	CM horizontal velocity (m/s)
FINALIST 1	8.95	8.75
FINALIST 2	9.16	9.21
FINALIST 3	9.42	9.44
FINALIST 4	9.44	9.26
FINALIST 5	9.80	9.47
FINALIST 6	9.65	9.62
FINALIST 7	9.37	9.32
FINALIST 8	8.84	9.21
FINALIST 9	9.21	8.89
MEAN ± SD	9.32 ± 0.31	9.24 ± 0.28

Table 4.22. Running velocity across up to two steps during the second sub-acceleration phase for each female finalist. (*Note: Step velocity was calculated using step length and step time, whereas the CM velocity was calculated from the full-body digitized data.*)

Figure 4.10 below displays the CM horizontal velocities of all finalists in the first sub-acceleration phase. The mean ± SD for the first sub-phase for the left-right and right-left was 9.07 ± 0.19 m/s, 9.11 ± 0.29 m/s.

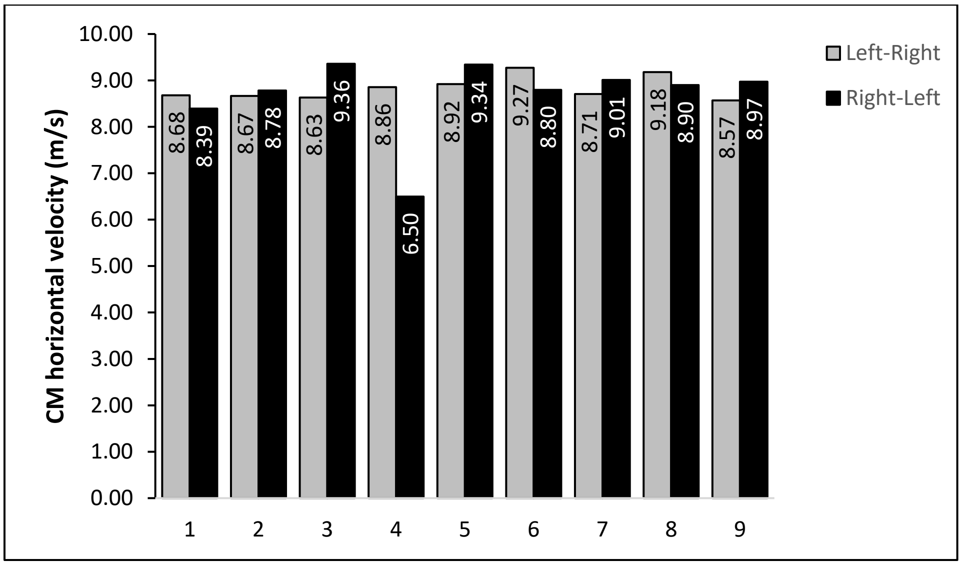


Figure 4.10. Individual center of mass (CM) horizontal velocities for each digitized step during the first sub-acceleration phase for each female finalist.

Figure 4.11 below displays the CM horizontal velocities of all finalists in the second sub-acceleration phase. The mean ± SD for the second sub-phase for the left-right and right-left was 9.31 ± 0.23 m/s, 9.24 ± 0.22 m/s.

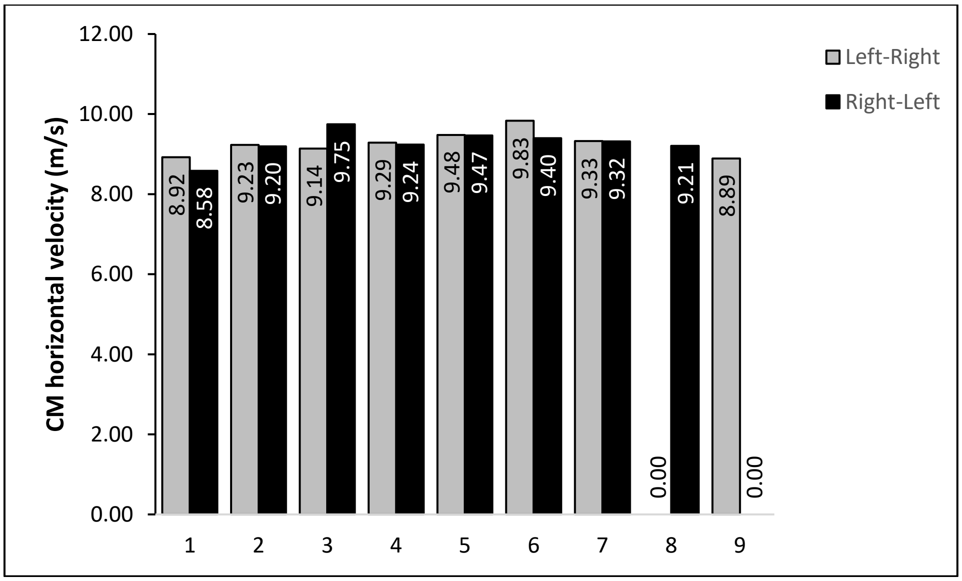


Figure 4.11. Individual center of mass (CM) horizontal velocities for each digitized step during the <u>second</u> sub-acceleration phase for each female finalist. (*Note: Values for the left-right of finalist 8 and right-left of finalist 9 were not attainable*.)

Figure 4.12 below displays the swing time of all finalists in the first sub-acceleration phase. The mean ± SD for the first sub-phase was 0.310 ± 0.02 s.

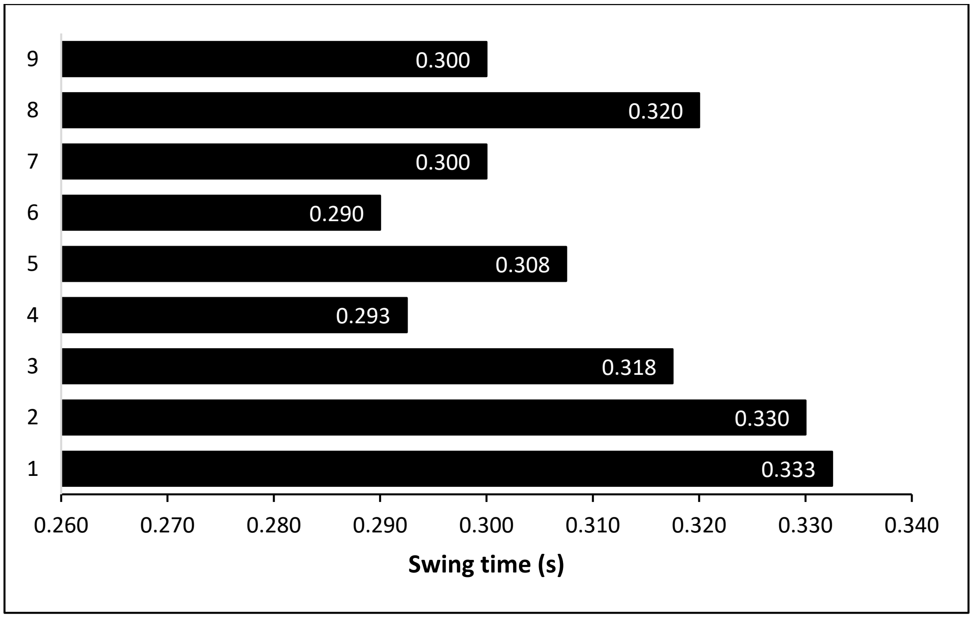


Figure 4.12. Swing time of up to two strides during the first sub-acceleration phase for each female finalist. For some athletes, the stride was left-left contact, for some, it was right-right contact.

Figure 4.13 below displays the swing time of all finalists in the second sub-acceleration phase. The mean ± SD for the second sub-phase was 0.311 ± 0.02 s.

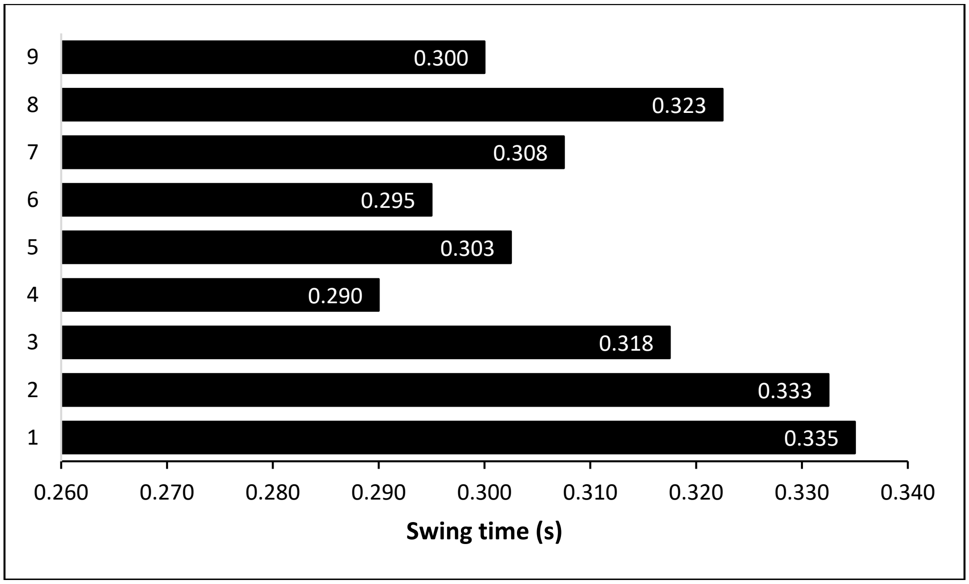


Figure 4.13. Swing time of up to two strides during the second sub-acceleration phase for each female finalist. For some athletes, the stride was left-left contact, for some, it was right-right contact.

Table 4.23 below displays the horizontal distance at touchdown and toe-off of each finalist in the first sub-acceleration phase. For the first sub-phase, the mean ± SD was 0.23 ± 0.03 m (DCM TD left), 0.27 ± 0.05 m (DCM TD right), 0.68 ± 0.03 m (DCM TO left), and 0.70 ± 0.05 m (DCM TO right).

	DCM TD (m)		DCM TO (m)	
Athlete	**Left**	**Right**	**Left**	**Right**
FINALIST 1	0.25	0.19	0.66	0.65
FINALIST 2	0.22	0.33	0.67	0.68
FINALIST 3	0.25	0.27	0.64	0.63
FINALIST 4	0.23	0.23	0.66	0.69
FINALIST 5	0.19	0.33	0.72	0.75
FINALIST 6	0.28	0.23	0.72	0.76
FINALIST 7	0.16	0.24	0.67	0.72
FINALIST 8	0.23	0.32	0.75	0.74
FINALIST 9	0.24	0.28	0.67	0.70
MEAN ± SD	0.23 ± 0.03	0.27 ± 0.05	0.68 ± 0.03	0.70 ± 0.05

Table 4.23. Horizontal distance from the point of ground contact to the body's CM at both touchdown (DCM TD) and toe-off (DCM TO). (*Note: Data displayed as absolute distance.*)

Table 4.24 below displays the horizontal distance at touchdown and toe-off of each finalist in the second sub-acceleration phase. For the second sub-phase, the mean ± SD was 0.29 ± 0.05 m (DCM TD left), 0.30 ± 0.03 m (DCM TD right), 0.65 ± 0.03 m (DCM TO left), and 0.66 ± 0.05 m (DCM TO right).

	DCM TD (m)		DCM TO (m)	
Athlete	**Left**	**Right**	**Left**	**Right**
FINALIST 1	0.32	0.25	0.61	0.59
FINALIST 2	0.33	0.32	-	0.65
FINALIST 3	0.30	0.30	0.62	0.61
FINALIST 4	0.32	0.28	0.65	0.69
FINALIST 5	0.21	0.31	0.68	0.66
FINALIST 6	0.31	0.28	0.68	0.73
FINALIST 7	0.23	0.28	0.66	0.65
FINALIST 8	-	0.34	-	0.72
FINALIST 9	0.29	-	0.66	-
MEAN ± SD	0.29 ± 0.05	0.30 ± 0.03	0.65 ± 0.03	0.66 ± 0.05

Table 4.24. Horizontal distance from the point of ground contact to the body's CM at both touchdown (DCM TD) and toe-off (DCM TO). (*Note: Data displayed as absolute distance and '-' indicate marks not attainable.*)

4.2.2.2 *Maximal Velocity Phase*

The following section of results shows key kinematic characteristics for each finalist during a selected calibrated volume of the race (40 – 47-m) in the maximal velocity phase.

Table 4.25 below displays the step length, step rate, and step width of each finalist in the maximal velocity phase. The mean ± SD was 2.16 ± 0.08 m, 4.82 ± 0.19 Hz, 0.14 ± 0.05 m, respectively. The correlation between the final race time and SL was r = -0.24; final race time and SR was r = -0.39; and final race time and SW was r = 0.02.

Athlete	Step length (m)	Step rate (Hz)	Step width (m)
FINALIST 1	2.28	4.94	0.20
FINALIST 2	2.14	4.84	0.13
FINALIST 3	2.14	4.82	0.15
FINALIST 4	2.13	4.94	0.12
FINALIST 5	2.13	4.85	0.11
FINALIST 6	2.14	4.95	0.13
FINALIST 7	2.26	4.46	0.07
FINALIST 8	2.03	5.01	0.15
FINALIST 9	2.19	4.57	0.23
MEAN ± SD	2.16 ± 0.08	4.82 ± 0.19	0.14 ± 0.05

Table 4.25. Mean step length, step rate, and step width across two steps for each finalist in the maximal velocity phase.

Figure 4.14 below displays the relationship between the step length and step rate of all finalists in the maximal velocity phase. The mean ± SD of this relationship was 10.40 ± 0.37 m·s^{-1} based on a multiple of SL and SR (SL x SR).

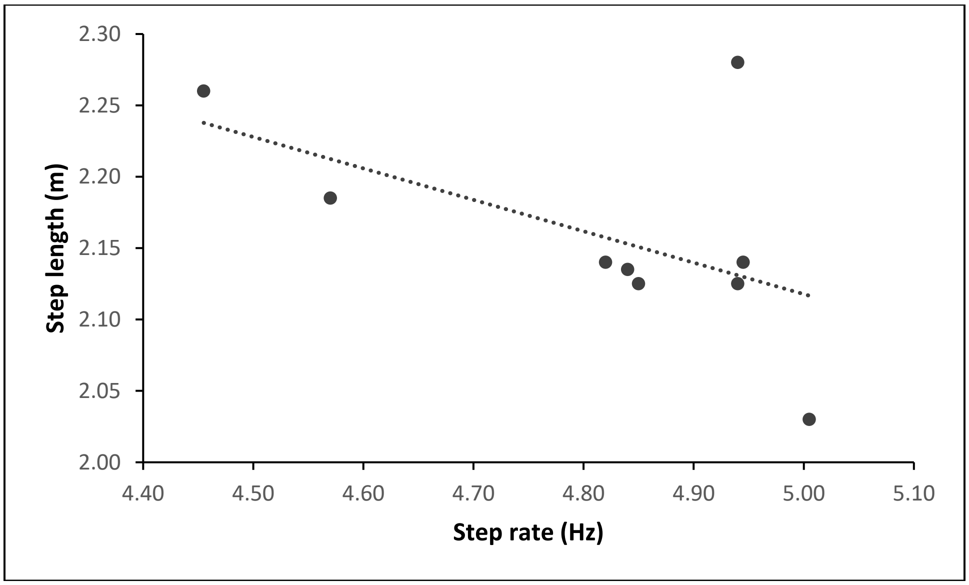


Figure 4.14. Scatterplot of the relationship between step rate and step length across two steps during maximal velocity phase for each female finalist.

Figure 4.15 below displays the contact time, flight time, and step time of all finalists in the maximal velocity phase. The mean ± SD for contact time: 0.09 ± 0.01 s (left), 0.10 ± 0.01 s (right); flight time 0.11 ± 0.01 (left), 0.12 ± 0.01 (right); step time 0.204 ± 0.01 (left), 0.213 ± 0.01 (right).

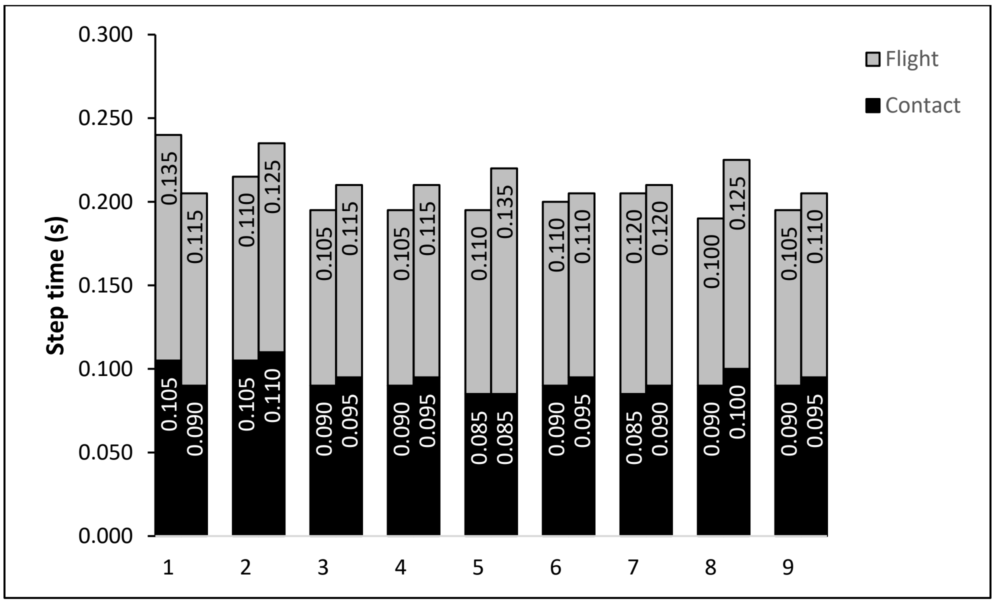


Figure 4.15. Contact, flight, and step times during maximal velocity running for each female finalist. Step time is the sum of contact and flight times. The left and right columns indicate the left and right legs of each athlete, respectively.

Table 4.26 below displays the mean step velocity and CM horizontal velocity of each finalist in the maximal velocity phase. The mean ± SD for each was 10.36 ± 0.38 m/s and 10.31 ± 0.32 m/s. The correlation between the final race time and step velocity (r = -0.67); and final race time and CM horizontal velocity (r = -0.75).

Athlete	Step velocity (m/s)	CM horizontal velocity (m/s)
FINALIST 1	9.95	9.91
FINALIST 2	10.04	9.99
FINALIST 3	11.23	10.95
FINALIST 4	10.54	10.55
FINALIST 5	10.29	10.48
FINALIST 6	10.49	10.31
FINALIST 7	10.29	10.32
FINALIST 8	10.24	10.20
FINALIST 9	10.15	10.09
MEAN ± SD	10.36 ± 0.38	10.31 ± 0.32

Table 4.26. Mean running velocity across two steps for each finalist. (*Note: Step velocity was calculated using step length and step time, whereas the CM velocity was calculated from the full-body digitized data.*)

Figure 4.16 below displays the CM horizontal velocities of all finalists in the maximal velocity phase. The mean ± SD for the left-right was 10.34 ± 0.37 m/s and 10.28 ± 0.30 m/s for the right-left.

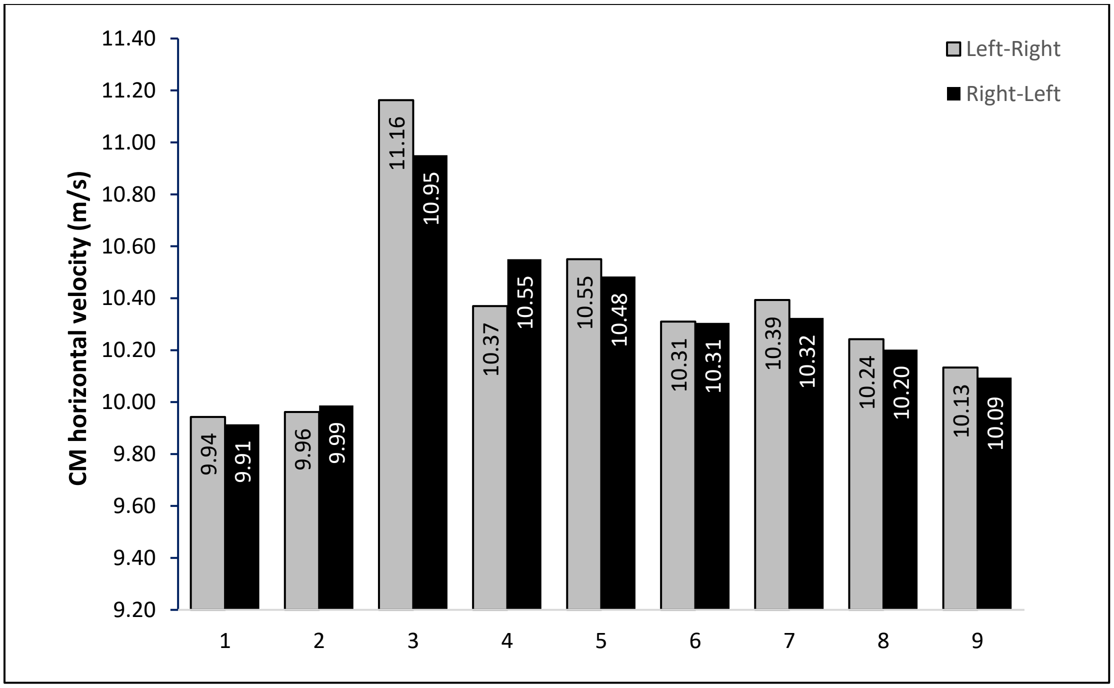


Figure 4.16. Individual center of mass (CM) horizontal velocities for each digitized step.

Figure 4.17 below displays the swing time of all finalists in the maximal velocity phase.

The mean ± SD was 0.324 ± 0.01 s.

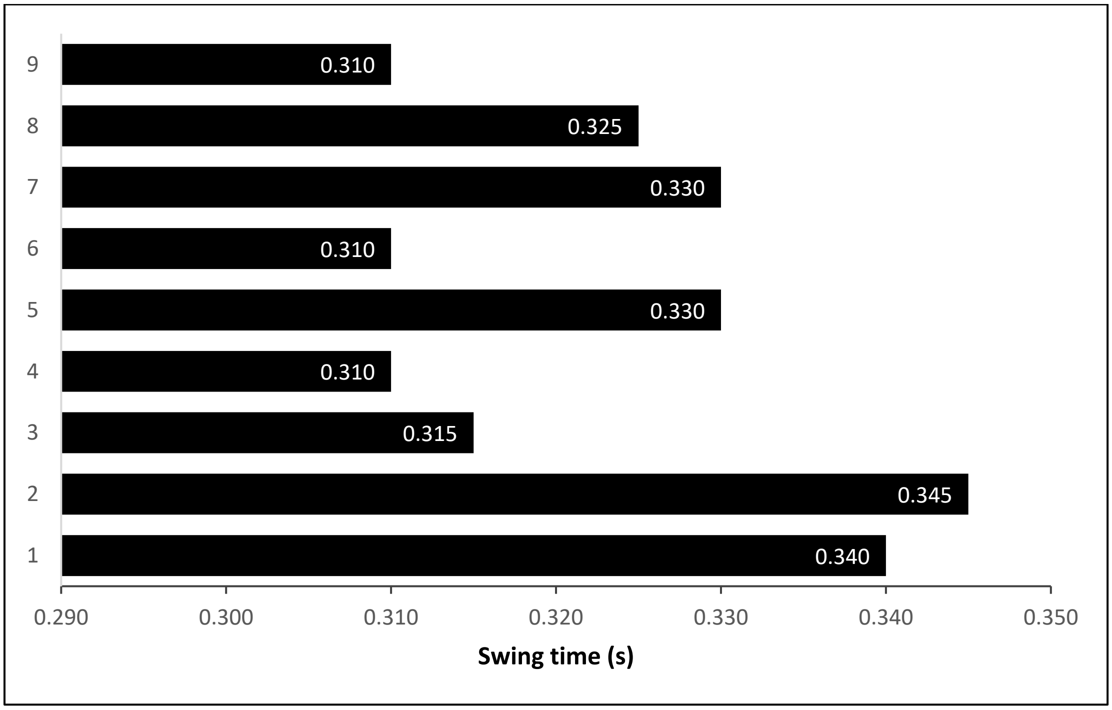


Figure 4.17. Swing time of one stride for each athlete. Some were left-left contact, while others were right-right contact.

Table 4.27 below displays horizontal distance at touchdown and toe-off of each finalist in the maximal velocity phase. The mean ± SD was 0.32 ± 0.03 m (DCM TD left), 0.34 ± 0.05 m (DCM TD right), 0.64 ± 0.04 m (DCM TO left), and 0.66 ± 0.07 m (DCM TO right).

	DCM TD (m)		DCM TO (m)	
Athlete	**Left**	**Right**	**Left**	**Right**
FINALIST 1	0.34	0.28	0.70	0.78
FINALIST 2	0.31	0.35	0.60	0.57
FINALIST 3	0.28	0.33	0.61	0.59
FINALIST 4	0.34	0.33	0.59	0.66
FINALIST 5	0.26	0.39	0.67	0.65
FINALIST 6	0.31	0.29	0.64	0.76
FINALIST 7	0.33	0.44	0.65	0.68
FINALIST 8	0.35	0.33	0.66	0.60
FINALIST 9	0.35	0.29	0.66	0.65
MEAN ± SD	0.32 ± 0.03	0.34 ± 0.05	0.64± 0.04	0.66 ± 0.07

Table 4.27. Horizontal distance from the point of ground contact to the body's CM at both touchdown (DCM TD) and toe-off (DCM TO). (*Note: Data displayed as an absolute distance.*)

Table 4.28 below displays center of mass (CM) contact distance of each finalist in the maximal velocity phase. The mean ± SD was 0.973 ± 0.06 (left) and 1.022 ± 0.06 (right).

	CM contact distance (m)	
Athlete	**Left**	**Right**
FINALIST 1	1.073	1.047
FINALIST 2	0.967	0.967
FINALIST 3	0.895	0.962
FINALIST 4	0.959	1.030
FINALIST 5	0.934	1.062
FINALIST 6	0.960	1.080
FINALIST 7	0.914	1.126
FINALIST 8	1.009	0.940
FINALIST 9	1.047	0.980
MEAN ± SD	0.973 ± 0.06	1.022 ± 0.06

Table 4.28. Contact distance the CM traveled during ground contact. (*Note: Data are presented as absolute distances.*)

To present a different perspective on touchdown kinematics, the following tables present horizontal and vertical velocities of each foot of the finalists upon striking the ground during maximal velocity running. Table 4.29 features foot horizontal velocity while Table 4.30 features foot vertical velocity.

Table 4.29 shows the mean ± SD were 2.86 ± 0.48 m/s (foot horizontal velocity pre-TD), 3.39 ± 0.95 m/s (foot horizontal velocity pre-TD), 3.13 ± 0.59 m/s (foot horizontal velocity pre-TD of both left and right), 2.00 ± 0.41 m/s (foot horizontal velocity TD), 2.43 ± 0.79 m/s (foot horizontal velocity TD), 2.21 ± 0.47 m/s (foot horizontal velocity TD of both left and right).

	Foot horizontal velocity pre-TD (m/s)		
Athlete	**Left**	**Right**	**Mean**
FINALIST 1	2.91	2.40	2.66
FINALIST 2	2.21	3.58	2.90
FINALIST 3	3.14	2.60	2.87
FINALIST 4	2.90	4.90	3.90
FINALIST 5	3.29	3.53	3.41
FINALIST 6	3.53	4.38	3.95
FINALIST 7	3.07	3.99	3.53
FINALIST 8	2.08	3.17	2.63
FINALIST 9	2.61	2.00	2.31
MEAN ± SD	2.86 ± 0.48	3.39 ± 0.95	3.13 ± 0.59

	Foot horizontal velocity TD (m/s)		
Athlete	**Left**	**Right**	**Mean**
FINALIST 1	2.06	1.63	1.85
FINALIST 2	1.36	2.57	1.97
FINALIST 3	2.08	1.74	1.91
FINALIST 4	1.86	3.62	2.74
FINALIST 5	2.64	2.89	2.77
FINALIST 6	2.42	3.04	2.73
FINALIST 7	2.07	2.99	2.53
FINALIST 8	1.46	2.17	1.82
FINALIST 9	2.03	1.20	1.61
MEAN ± SD	2.00 ± 0.41	2.43 ± 0.79	2.21 ± 0.47

Table 4.29. Horizontal velocity of the foot center of mass at the instance before touchdown and the instant of touchdown. Data presented for left and right feet individually as well as a left-right means at each instant. (*Note: The positive velocities observed indicate that the foot is moving forward relative to the running surface.*)

To present a different perspective to touchdown kinematics, the following tables present horizontal and vertical velocities of each foot of the finalists upon striking the ground during maximal velocity running.

Table 4.30 shows the mean ± SD were -3.13 ± 0.28 m/s (foot vertical velocity pre-TD) and -2.99 ± 0.41 m/s (foot vertical velocity pre-TD), -3.06 ± 0.24 m/s (foot vertical velocity pre-TD of both left and right), -2.62 ± 0.40 m/s (foot vertical velocity TD), -2.42 ± 0.41 m/s (foot vertical velocity TD), -2.52 ± 0.24 m/s (foot vertical velocity TD of both left and right).

	Foot vertical velocity pre-TD (m/s)		
Athlete	**Left**	**Right**	**Mean**
FINALIST 1	-2.91	-3.28	-3.09
FINALIST 2	-2.90	-3.04	-2.97
FINALIST 3	-3.16	-3.21	-3.18
FINALIST 4	-2.99	-2.84	-2.92
FINALIST 5	-3.74	-3.47	-3.60
FINALIST 6	-3.15	-2.76	-2.95
FINALIST 7	-2.98	-2.68	-2.83
FINALIST 8	-2.91	-3.44	-3.18
FINALIST 9	-3.39	-2.23	-2.81
MEAN ± SD	-3.13 ± 0.28	-2.99 ± 0.41	-3.06 ± 0.24
	Foot vertical velocity TD (m/s)		
Athlete	**Left**	**Right**	**Mean**
FINALIST 1	-2.28	-2.65	-2.47
FINALIST 2	-2.29	-2.45	-2.37
FINALIST 3	-2.60	-2.48	-2.54
FINALIST 4	-2.39	-2.50	-2.44
FINALIST 5	-3.25	-2.89	-3.07
FINALIST 6	-3.15	-2.21	-2.68
FINALIST 7	-2.52	-2.18	-2.35
FINALIST 8	-2.18	-2.86	-2.52
FINALIST 9	-2.94	-1.55	-2.24
MEAN ± SD	-2.62 ± 0.40	-2.42 ± 0.41	-2.52 ± 0.24

Table 4.30. Vertical velocity of the foot center of mass at the instance before touchdown and the instant of touchdown. Data presented for left and right feet individually as well as a left-right means at each instant. (*Note: The negative velocities observed indicate downward movement of the foot CM.*)

The following section describes key joint angles for the critical instants of touchdown during maximal velocity. Figure 4.18 provides a visual depiction of these angles. Correlations between four specific postural characteristics and speed times reached within the 30-m fly were calculated: trunk (r = 0.13), hip (r = -0.15), knee (r = 0.21), ankle (r = 0.67). Correlations between four specific postural characteristics and final race times were also calculated: trunk (r = -0.29), hip (r = -0.26), knee (r = 0.31), and ankle (r = 0.52).

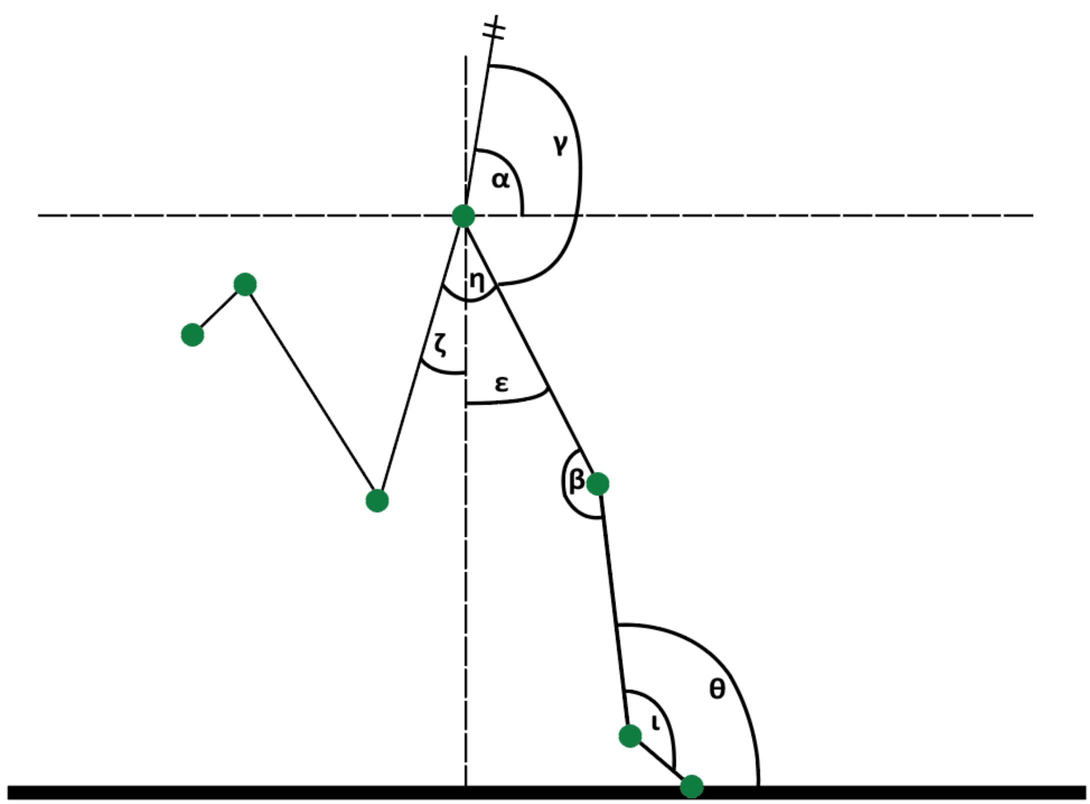


Figure 4.18. Body schematic denoting joint angles measured at touchdown. This does not represent any athlete's posture but is merely for illustrative purposes (*adapted from Bissas et al., 2018a; Bissas et al., 2018b*).

	FINALIST 1		FINALIST 2		FINALIST 3	
	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)
Trunk [α]	80.5	72.9	76.3	81.8	83.3	69.5
Knee [β]	153.5	146.4	145.7	137.3	152.9	134.3
Hip [γ]	147.0	128.3	139.6	133.4	158.9	125.2
Ankle [ι]	114.7	111.1	111.8	107.6	114.4	-

Table 4.31. Joint angles at *touchdown* for finalists 1, 2, and 3. Key select angles variables are defined as: α - trunk; β – knee; γ - hip (contact); ι – ankle. (*Note: The 2-D schematic should not be used as a model to combine angles as different landmarks have been used for defining certain angles. Dash, '-', represents an angle value that was impossible to obtain due to technical limitation.*)

	FINALIST 4		FINALIST 5		FINALIST 6	
	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)
Trunk [α]	75.4	67.4	-	-	-	-
Knee [β]	151.3	150.5	142.1	131.3	157.1	141.3
Hip [γ]	144.3	132.8	142.8	131.4	142.9	126.0
Ankle [ι]	109.5	103.4	106.1	99.1	111.6	97.6

Table 4.32. Joint angles at *touchdown* for finalists 4, 5, and 6. Key select angles variables are defined as: α - trunk; β – knee; γ - hip (contact); ι – ankle. (*Note: The 2-D schematic should not be used as a model to combine angles as different landmarks have been used for defining certain angles. Dash, '-', represents an angle value that was impossible to obtain due to technical limitation.*)

	FINALIST 7		FINALIST 8		FINALIST 9	
	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)
Trunk [α]	77.4	80.3	77.9	82.5	72.1	75.0
Knee [β]	159.3	150.3	164.5	159.0	155.2	147.5
Hip [γ]	154.2	143.1	155.7	150.6	136.3	128.6
Ankle [ι]	111.6	124.0	117.9	105.7	120.9	109.4

Table 4.33. Joint angles at *touchdown* for finalists 7, 8, and 9. Key select angles variables are defined as: α - trunk; β – knee; γ - hip (contact); ι – ankle. (*Note: The 2-D schematic should not be used as a model to combine angles as different landmarks have been used for defining certain angles.*)

The following section describes key joint angles for the critical instants of toe-off during maximal velocity. Figure 4.19 provides a visual depiction of these angles. Correlations between four specific postural characteristics and speed times reached within the 30-m fly were calculated: trunk (r = 0.29), hip (r = 0.14), knee (r = 0.20), ankle (r = -0.02). Correlations between four specific postural characteristics and final race times were also calculated: trunk (r = -0.13), hip (r = 0.50), knee (r = 0.03), and ankle (r = 0.12).

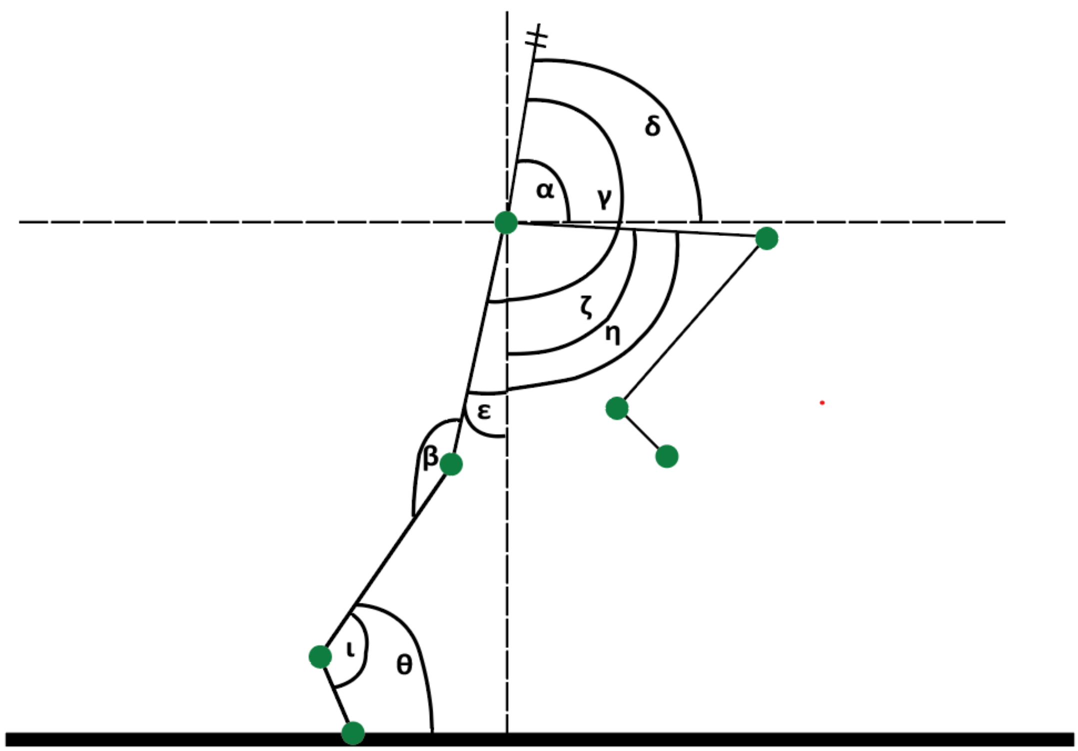


Figure 4.19. Body schematic denoting joint angles measured at toe-off. This does not represent any athlete's posture but is merely for illustration purposes (*adapted from Bissas et al., 2018a; Bissas et al., 2018b*).

	FINALIST 1		FINALIST 2		FINALIST 3	
	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)
Trunk [α]	81.6	82.3	84.1	88.4	80.7	81.4
Knee [β]	153.8	145.5	155.8	157.1	150.7	153.3
Hip [γ]	201.1	189.7	203.4	202.7	206.1	207.1
Ankle [ι]	147.6	144.3	140.9	132.6	145.7	146.3

Table 4.34. Joint angles at *toe-off* for finalists 1, 2, and 3. Key select angles variables are defined as: α - trunk; β – knee; γ - hip (contact); ι – ankle. (*Note: The 2-D schematic should not be used as a model to combine angles as different landmarks have been used for defining certain angles.*)

	FINALIST 4		FINALIST 5		FINALIST 6	
	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)
Trunk [α]	75.2	76.6	-	-	-	-
Knee [β]	151.8	151.0	146.4	139.8	142.1	146.8
Hip [γ]	188.6	190.0	197.7	196.6	194.0	192.3
Ankle [ι]	142.8	141.6	136.6	133.8	131.0	134.7

Table 4.35. Joint angles at *toe-off* for finalists 4, 5, and 6. Key select angles variables are defined as: α - trunk; β – knee; γ - hip (contact); ι – ankle. (*Note: The 2-D schematic should not be used as a model to combine angles as different landmarks have been used for defining certain angles. Dash, '-', represents an angle value that was impossible to obtain due to technical limitation.*)

	FINALIST 7		FINALIST 8		FINALIST 9	
	Left (°)	**Right (°)**	**Left (°)**	**Right (°)**	**Left (°)**	**Right (°)**
Trunk [α]	79.2	86.3	82.6	88.3	77.4	79.1
Knee [β]	157.9	150.3	152.9	140.0	142.4	139.9
Hip [γ]	204.9	207.8	201.3	197.5	191.5	192.1
Ankle [ι]	134.0	131.8	142.3	129.3	135.4	128.8

Table 4.36. Joint angles at *toe-off* for finalist 7, 8, and 9. Key select angles variables are defined as: α - trunk; β – knee; γ - hip (contact); ι – ankle. (*Note: The 2-D schematic should not be used as a model to combine angles as different landmarks have been used for defining certain angles.*)

Table 4.37 below shows the minimum knee joint angle and change in those knee angles at touchdown to minimum knee angle during left and right contacts for each finalist during the maximal velocity phase. The mean ± SD for the minimum knee joint angle was 145.3 ± 5.91° (left), 134.9 ± 2.78° (right) with a change in knee angle of 8.2 ± 6.44° (left) and 9.4 ± 8.30° (right).

	Minimum knee angle (°)		Δ knee angle (°)	
Athlete	**Left**	**Right**	**Left**	**Right**
FINALIST 1	152.4	137.9	1.1	8.5
FINALIST 2	138.4	133.2	7.3	4.1
FINALIST 3	144.5	134.4	8.4	0.0
FINALIST 4	147.1	129.9	4.3	20.6
FINALIST 5	137.3	134.4	4.9	3.1
FINALIST 6	146.1	134.2	11.0	7.1
FINALIST 7	155.1	137.3	4.1	13.0
FINALIST 8	141.2	139.0	23.3	20.0
FINALIST 9	145.7	133.5	9.5	14.0
MEAN ± SD	145.3 ± 5.91	134.9 ± 2.78	8.2 ± 6.44	9.4 ± 8.30

Table 4.37. Minimum knee joint and change in knee angle from touchdown. (*Note: Knee angles shown here are represented by angle 'β' in Figure 4.18.*)

Table 4.38 below shows the minimum ankle joint angle and change in those ankle angles at touchdown to minimum ankle angle during left and right contacts for each finalist during the maximal velocity phase. The mean ± SD for the minimum ankle joint angle was 86.0 ± 2.60° (left), 84.9 ± 4.34° (right) with a change in ankle angle of 27.2 ± 4.72° (left) and 22.2 ± 7.25° (right).

	Minimum ankle angle (°)		Δ ankle angle (°)	
Athlete	**Left**	**Right**	**Left**	**Right**
FINALIST 1	90.2	86.0	24.5	25.1
FINALIST 2	84.6	83.2	27.2	24.4
FINALIST 3	84.0	84.0	30.4	-
FINALIST 4	84.1	80.3	25.4	23.1
FINALIST 5	83.4	86.8	22.7	12.3
FINALIST 6	86.3	87.8	25.3	9.7
FINALIST 7	90.3	93.6	21.3	30.4
FINALIST 8	85.3	79.0	32.6	26.7
FINALIST 9	85.4	83.7	35.5	25.6
MEAN ± SD	86.0 ± 2.60	84.9 ± 4.34	27.2 ± 4.72	22.2 ± 7.25

Table 4.38. Minimum knee joint and change in knee angle from toe-off. (*Note: Ankle angles shown here are represented by angle 'ι' in Figure 4.19. Dash, '-', represents an angle value that was impossible to obtain due to technical limitation.*)

4.3 JUMP DISCIPLINE – LONG JUMP

4.3.1 *JUMP RESULTS*

The following sections of results include data from the NCAA Women's Long Jump.

A total of 96 collegiate jumpers qualified for a chance to compete in the final 3 rounds of the NCAA Women's Long Jump. The West and East Regions each had 48 competitors jump in 4 flights of 12 jumpers in the First Round of the NCAA Championships. Each region advanced 12 competitors, totaling 24 jumpers, to the Preliminary Rounds (Round 1, Round 2, and Round 3) in Eugene, Oregon. The top nine jumps achieved from the Preliminary rounds are given three more jumps in the Final Rounds (Round 4, Round 5, and Round 6).

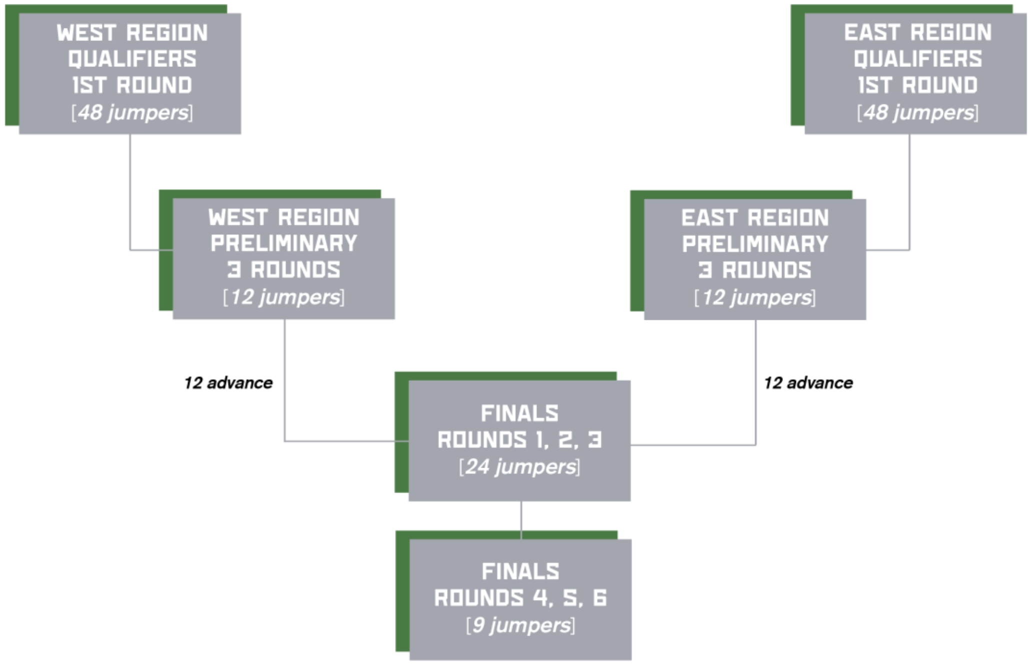


Figure 4.20. Advancement in the rounds of the NCAA Women's Long Jump.

Results include Preliminary Rounds (1, 2, 3) and Final Rounds (4, 5, 6) of the Women's Long Jump, with a more in-depth look at temporal and kinematic characteristics of the top seven finalists during calibrated volume in specific stages of the runway approach to the take-off. For record purposes, including meet, collegiate, and facility records, 'legal wind' jumps are denoted in green and 'wind-aided' jumps are denoted in red.

Table 4.39. Abbreviations used for jumps.

F	Foul	SB	Season's best time
+/-	+ = positive; - = negative	PB	Personal best time

Table 4.40 below shows the official best distance of each athlete (48 competitors) from the West Region NCAA First Round of the Women's Long Jump alongside a comparison with their personal and season's bests. The mean jump distance of all competitors was 6.21 meters; the mean difference compared with season's bests was -0.17 meters; and the mean difference compared with personal bests was 0.06 meters.

Athlete	Rank	Wind (m/s)	Official mark (m)	SB [2021] (m)	Compared to SB (m)	PB (m)	Compared to PB (m)
JUMPER 1	77	+1.9	5.96	6.21	-0.25	6.02	0.19
JUMPER 2	98	+2.3	5.80	6.12	-0.32	6.12	0.00
JUMPER 3	94	+2.3	5.30	6.14	-0.84	6.14	0.00
JUMPER 4	96	+2.6	5.95	6.13	-0.18	6.27	-0.14
JUMPER 5	98	+3.1	5.82	6.12	-0.30	6.12	0.00
JUMPER 6	68	+1.7	6.35	6.24	0.11	6.24	0.00
JUMPER 7	83	+2.5	6.06	6.20	-0.14	6.20	0.00
JUMPER 8	91	+3.5	6.18	6.16	0.02	6.16	0.00
JUMPER 9	92	+3.2	6.03	6.15	-0.12	6.15	0.00
JUMPER 10	77	+2.3	6.26	6.21	0.05	6.21	0.00
JUMPER 11	104	+3.0	5.91	6.11	-0.20	5.96	0.15
JUMPER 12	88	+3.5	6.19	6.17	0.02	6.17	0.00
JUMPER 13	65	+1.8	5.61	6.25	-0.64	6.08	0.17
JUMPER 14	55	+0.7	6.16	6.29	-0.13	6.29	0.00
JUMPER 15	68	+3.6	5.92	6.24	-0.32	6.43	-0.19
JUMPER 16	55	+2.7	6.33	6.29	0.04	6.29	0.00
JUMPER 17	51	+2.9	6.18	6.30	-0.12	6.20	0.10
JUMPER 18	65	+2.2	5.92	6.25	-0.33	6.25	0.00
JUMPER 19	63	+3.2	5.83	6.26	-0.43	6.27	-0.01
JUMPER 20	59	-	F	6.28	-	6.28	0.00

JUMPER 21	63	+1.9	6.41	6.26	0.15	6.04	0.22
JUMPER 22	51	+2.5	6.10	6.30	-0.20	6.55	-0.25
JUMPER 23	51	+2.3	6.39	6.30	0.09	6.30	0.00
JUMPER 24	55	+2.5	6.07	6.29	-0.22	6.29	0.00
JUMPER 25	24	+2.3	6.24	6.47	-0.23	6.47	0.00
JUMPER 26	43	+3.0	6.55	6.35	0.20	6.35	0.00
JUMPER 27	20	+2.6	6.50	6.51	-0.01	6.42	0.09
JUMPER 28	40	+2.8	6.28	6.36	-0.08	6.36	0.00
JUMPER 29	26	+1.4	6.19	6.45	-0.26	6.32	0.13
JUMPER 30	34	+3.3	6.25	6.39	-0.14	6.39	0.00
JUMPER 31	49	+2.3	6.73	6.32	0.41	6.42	-0.10
JUMPER 32	28	+3.2	6.30	6.43	-0.13	6.38	0.05
JUMPER 33	45	+4.0	6.18	6.34	-0.16	6.34	0.00
JUMPER 34	24	-	F	6.47	-	6.13	0.34
JUMPER 35	40	+4.1	6.32	6.36	-0.04	6.31	0.05
JUMPER 36	26	+2.4	6.35	6.45	-0.10	6.09	0.36
JUMPER 37	9	+1.3	6.44	6.61	-0.17	6.61	0.00
JUMPER 38	16	+2.7	6.35	6.53	-0.18	6.53	0.00
JUMPER 39	2	+2.9	6.95	6.96	-0.01	6.96	0.00
JUMPER 40	14	+2.3	5.49	6.56	-1.07	6.56	0.00
JUMPER 41	18	+2.3	6.29	6.52	-0.23	6.52	0.00
JUMPER 42	6	-	F	6.75	-	6.47	0.28
JUMPER 43	10	+3.8	6.11	6.59	-0.48	6.55	0.04
JUMPER 44	10	+2.3	6.81	6.59	0.22	6.59	0.00
JUMPER 45	1	+2.5	6.86	7.14	-0.28	7.14	0.00
JUMPER 46	13	+1.0	6.43	6.57	-0.14	6.47	0.10
JUMPER 47	4	+2.3	6.58	6.81	-0.23	6.81	0.00
JUMPER 48	5	+2.7	6.67	6.76	-0.09	6.76	0.00

Table 4.40. Comparison of jump distance, season best, and personal best from Women's Long Jump First Round in the West Region. Negative values represent a shorter jump in the 2021 NCAA Championships rounds compared with the SB and PB. (*Note: Temperature, wind, humidity, pressure, and altitude not recorded at this location.*)

Table 4.41 below shows the official best distance of each athlete (48 competitors) from the East Region NCAA First Round of the Women's Long Jump alongside a comparison with their personal and season's bests. The mean jump distance of all competitors was 6.23 meters; the mean difference compared with season's bests was -0.25 meters; and the mean difference compared with personal bests was 0.03 meters.

Athlete	Rank	Wind (m/s)	Official mark (m)	SB [2021] (m)	Compared to SB	PB (m)	Compared to PB (m)
JUMPER 1	84	-0.7	6.05	6.19	-0.14	6.17	0.02
JUMPER 2	92	-0.5	5.46	6.15	-0.69	6.34	-0.19
JUMPER 3	94	-0.3	5.88	6.14	-0.26	6.02	0.12
JUMPER 4	88	-0.3	6.09	6.17	-0.08	6.06	0.11
JUMPER 5	98	-0.1	5.73	6.12	-0.39	6.12	0.00
JUMPER 6	98	+1.0	5.93	6.12	-0.19	6.12	0.00
JUMPER 7	84	-0.1	5.85	6.19	-0.34	6.08	0.11
JUMPER 8	104	+0.1	5.85	6.11	-0.26	6.11	0.00
JUMPER 9	114	+0.1	5.66	6.08	-0.42	6.08	0.00
JUMPER 10	108	+1.5	6.06	6.10	-0.04	6.10	0.00
JUMPER 11	87	-0.6	5.71	6.18	-0.47	6.09	0.09
JUMPER 12	96	+0.9	5.50	6.13	-0.63	6.05	0.08

JUMPER 13	59	-0.1	6.04	6.28	-0.24	6.28	0.00
JUMPER 14	68	-0.8	6.12	6.24	-0.12	6.24	0.00
JUMPER 15	68	-0.1	6.12	6.24	-0.12	6.24	0.00
JUMPER 16	68	+0.7	6.16	6.24	-0.08	6.24	0.00
JUMPER 17	77	+1.3	6.27	6.21	0.06	6.21	0.00
JUMPER 18	76	+0.4	5.99	6.22	-0.23	6.22	0.00
JUMPER 19	68	+0.1	6.07	6.24	-0.17	6.24	0.00
JUMPER 20	77	+0.2	5.91	6.21	-0.30	6.21	0.00
JUMPER 21	84	+0.6	5.77	6.19	-0.42	6.17	0.02
JUMPER 22	65	-0.4	5.86	6.25	-0.39	6.39	-0.14
JUMPER 23	59	-	F	6.28	-	6.28	0.00
JUMPER 24	62	+0.3	5.99	6.27	-0.28	6.19	0.08
JUMPER 25	37	+0.0	5.89	6.38	-0.49	6.38	0.00
JUMPER 26	50	+0.1	5.73	6.31	-0.58	6.31	0.00
JUMPER 27	34	-0.1	5.53	6.39	-0.86	6.11	0.28
JUMPER 28	40	-0.3	6.16	6.36	-0.20	6.37	-0.01
JUMPER 29	37	-	F	6.38	-	6.35	0.03
JUMPER 30	31	+0.6	6.48	6.41	0.07	6.41	0.00
JUMPER 31	55	+0.9	6.20	6.29	-0.09	6.28	0.01
JUMPER 32	47	+1.0	6.05	6.33	-0.28	6.29	0.04
JUMPER 33	34	-0.5	6.21	6.39	-0.18	6.39	0.00
JUMPER 34	45	+1.5	6.26	6.34	-0.08	6.26	0.08
JUMPER 35	43	-	DNS	6.35	-	6.35	0.00
JUMPER 36	33	-0.7	5.68	6.40	-0.72	6.40	0.00
JUMPER 37	23	+3.0	6.58	6.49	0.09	6.49	0.00
JUMPER 38	21	-0.2	6.05	6.50	-0.45	6.50	0.00
JUMPER 39	21	+1.2	6.53	6.50	0.03	6.50	0.00
JUMPER 40	3	+2.5	6.63	6.83	-0.20	6.83	0.00
JUMPER 41	30	+1.0	6.43	6.42	0.01	6.42	0.00
JUMPER 42	14	-0.3	6.23	6.56	-0.33	6.56	0.00

JUMPER 43	7	+1.3	6.64	6.71	-0.07	6.68	0.03
JUMPER 44	16	+1.1	6.47	6.53	-0.06	6.71	-0.18
JUMPER 45	18	+2.0	6.22	6.52	-0.30	6.29	0.23
JUMPER 46	12	+0.3	6.37	6.58	-0.21	6.58	0.00
JUMPER 47	8	+1.5	6.63	6.65	-0.02	6.65	0.00
JUMPER 48	28	+0.5	6.19	6.43	-0.24	6.27	0.16

Table 4.41. Comparison of jump distance, season best, and personal best from Women's Long Jump First Round in the East Region. Negative values represent a shorter jump in the 2021 NCAA Championships rounds compared with the SB and PB. (*Note: Temperature, wind, humidity, pressure, and altitude not recorded at this location.*)

Table 4.42 below shows the official best distance of each athlete (24 competitors) from Flight 1 and 2 in Preliminary Rounds 1, 2, and 3 of the Women's Long Jump alongside a comparison with their personal and season's bests. The mean jump distance of all competitors was 6.25 meters; and the mean difference compared with season's bests was -0.35 meters; the mean difference compared with personal bests was 0.03 meters.

Athlete	Rank	Wind (m/s)	Official mark (m)	SB [2021] (m)	Compared to SB	PB (m)	Compared to PB (m)
JUMPER 1	3	+1.2	6.61	6.83	-0.22	6.83	0.00
JUMPER 2	4	+1.0	6.37	6.81	-0.44	6.81	0.00
JUMPER 3	19	+0.8	6.35	6.53	-0.18	6.53	0.00
JUMPER 4	11	+0.7	6.50	6.59	-0.09	6.59	0.00
JUMPER 5	1	+1.1	6.52	7.14	-0.62	7.14	0.00
JUMPER 6	8	+0.1	6.45	6.71	-0.26	6.68	0.03
JUMPER 7	5	+0.5	6.36	6.76	-0.40	6.76	0.00
JUMPER 8	13	+0.3	6.19	6.58	-0.39	6.49	0.09
JUMPER 9	26	+0.2	6.29	6.48	-0.19	6.48	0.00
JUMPER 10	2	+1.5	6.36	6.96	-0.60	6.96	0.00
JUMPER 11	9	-0.3	6.09	6.65	-0.56	6.65	0.00
JUMPER 12	7	+0.4	6.24	6.73	-0.49	6.54	0.19
JUMPER 13	34	+1.1	5.76	6.41	-0.65	6.41	0.00
JUMPER 14	13	+2.5	6.46	6.58	-0.12	6.58	0.00
JUMPER 15	64	+1.1	6.01	6.27	-0.26	6.27	0.00
JUMPER 16	37	+0.6	6.02	6.39	-0.37	6.30	0.09
JUMPER 17	18	+0.8	6.12	6.55	-0.43	6.35	0.20
JUMPER 18	15	+1.1	6.26	6.57	-0.31	6.47	0.10
JUMPER 19	16	+0.6	6.36	6.56	-0.20	6.56	0.00
JUMPER 20	49	+0.7	5.88	6.34	-0.46	6.26	0.08

JUMPER 21	24	-0.3	6.35	6.51	-0.16	6.42	0.09
JUMPER 22	10	+0.1	6.28	6.61	-0.33	6.61	0.00
JUMPER 23	31	+0.2	6.28	6.43	-0.15	6.43	0.00
JUMPER 24	19	-0.3	5.99	6.53	-0.54	6.71	-0.18

Table 4.42. Comparison of jump distance, season best, and personal best from Women's Long Jump Preliminary Rounds 1, 2, and 3. Negative values represent a shorter jump in the 2021 NCAA Championships rounds/finals compared with the SB and PB. (*Note: 65°F, wind 2 mph WNW, humidity 56%, pressure 30.09in, and altitude 470ft (jump conditions adapted from flashresults.com).*)

4.3.2 *JUMP FINALISTS*

Table 4.43 below shows the official best distance of each athlete (top 9 competitors) from the combined flights, Final Rounds 4, 5, and 6 of the Women's Long Jump alongside a comparison with their personal and season's bests. The mean jump distance of all competitors was 6.52 meters; and the mean difference compared with season's bests was -0.25 meters; the mean difference compared with personal bests was 0.003 meters.

Athlete	Rank	Wind (m/s)	Official mark (m)	SB [2021] (m)	Compared to SB (m)	PB (m)	Compared to PB (m)
JUMPER 1	3	+1.5	6.65	6.83	-0.18	6.83	0.00
JUMPER 2	1	+1.0	6.70	7.14	-0.44	7.14	0.00
JUMPER 3	11	+0.7	6.50	6.59	-0.09	6.59	0.00
JUMPER 4	13	+0.3	6.58	6.58	0.00	6.58	0.00
JUMPER 5	8	+0.1	6.45	6.71	-0.26	6.68	0.03
JUMPER 6	4	-0.5	6.39	6.81	-0.42	6.81	0.00
JUMPER 7	2	+0.2	6.68	6.96	-0.28	6.96	0.00
JUMPER 8	5	+0.5	6.36	6.76	-0.40	6.76	0.00
JUMPER 9	16	+0.6	6.36	6.56	-0.20	6.56	0.00
MEAN ± SD			6.52 ± 0.14	6.77 ± 0.19		6.77 ± 0.19	

Table 4.43. Comparison of jump distance, season best, and personal best from Women's Long Jump Final Rounds 4, 5, and 6. Negative values represent a shorter jump in the 2021 NCAA Championship rounds/finals compared with the SB and PB. (*Note: 65°F, wind 2 mph WNW, humidity 56%, pressure 30.09in, and altitude 470ft (jump conditions adapted from flashresults.com).*)

The following results present the progression of distance marks posted by each finalist in each round taken to reach the final rounds of the long jump (chart and table format). Distances for each round are given in meters (m).

Figure 4.21 and Table 4.44 shows the mean official mark for each round was 6.64 ± 0.23 (First Round), 6.44 ± 0.09 (Preliminary Rounds 1-3), and 6.46 ± 0.20 (Final Rounds 4-6).

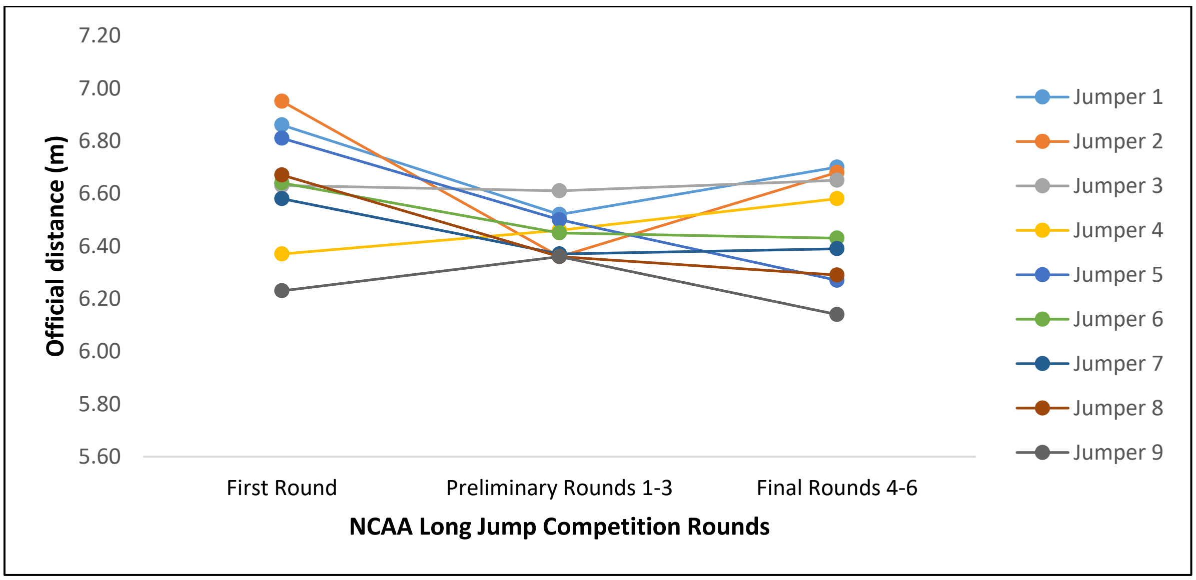


Figure 4.21. Figure presentation of official distance marks posted in each round leading into the final rounds by each jump finalist.

Athlete	First Round (m)	Preliminary Rounds 1-3 (m)	Final Rounds 4-6 (m)
JUMPER 1	6.86	6.52	6.70
JUMPER 2	6.95	6.36	6.68
JUMPER 3	6.37	6.61	6.65
JUMPER 4	6.37	6.46	6.58
JUMPER 5	6.81	6.50	6.27
JUMPER 6	6.64	6.45	6.43
JUMPER 7	6.58	6.37	6.39
JUMPER 8	6.67	6.36	6.29
JUMPER 9	6.23	6.36	6.14
MEAN ± SD	6.64 ± 0.23	6.44 ± 0.09	6.46 ± 0.20

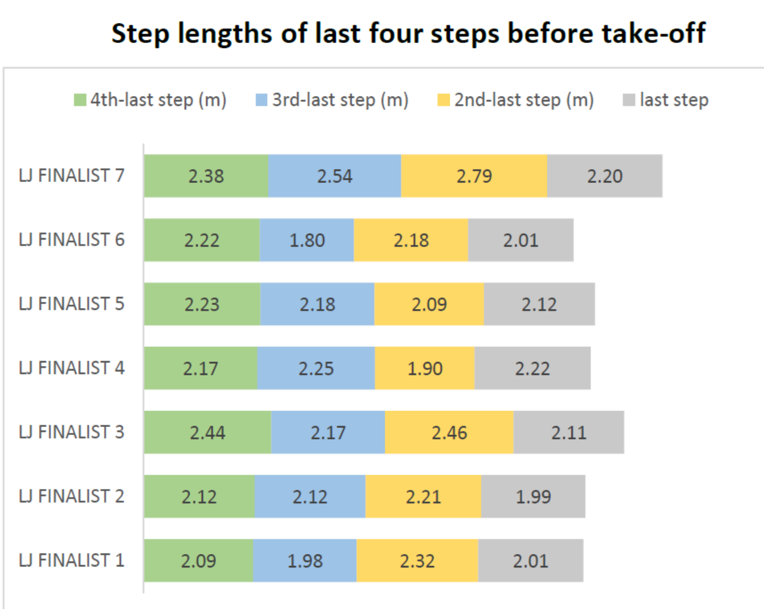
Table 4.44. Table presentation of best official mark posted in rounds leading into the final by each jump finalist.

4.3.2.1 *Approach Phase*

The following section of results focuses on 7 of 9 finalists (two runways were used in competition for Preliminary Rounds (1, 2, 3) and Finals Rounds (4, 5, 6); finalists stay on the same runway for all rounds; only one runway was calibrated).

Table 4.45 below shows the step lengths of the best individual jump of 7 finalists during their last 4 steps before the take-off board. Percentage change between fourth- to last, third- to last, and second- to last are presented as well. The mean change from fourth-last to third-last and third-last to second-last, was an increase of -4% and 7%, and -7%, respectively.

The mean ± SD for step length for the fourth-last step was 2.24 ± 0.13 m, the third-last step was 2.15 ± 0.23 m, the second-last step was 2.28 ± 0.29 m, and the last step was 2.09 ± 0.09 m.



Change in step length		
4th last / 3rd last (%)	3rd last / 2nd last (%)	2nd last / last) (%)
+7	+10	-21
-19	+21	-8
-2	-4	+1
+4	-16	+16
-11	13	-14
0	+4	-10
-5	+17	-13

MEAN ± SD	2.24 ± 0.13	2.15 ± 0.23	2.28 ± 0.29	2.09 ± 0.09

Table 4.45. Step length characteristics of the last 4 steps of the best individual jump for 7 finalists. *LJ Finalist = long jump finalist.*

Table 4.46 below shows the step rate of the best individual jump of 7 finalists during their last 4 steps before the take-off board. The mean ± SD for step rate time for the fourth-last step was 4.68 ± 0.45 Hz, the third-last step was 4.38 ± 0.52 Hz, the second-last step was 4.38 ± 0.52 Hz, and the last step was 4.53 ± 0.52 Hz.

Athlete	4th-last step (Hz)	3rd-last step (Hz)	2nd-last step (Hz)	Last step (Hz)
LJ FINALIST 1	4.69	5.00	4.55	5.17
LJ FINALIST 2	4.55	4.55	5.56	4.29
LJ FINALIST 3	4.69	3.85	5.00	3.95
LJ FINALIST 4	4.55	4.41	5.77	5.17
LJ FINALIST 5	4.69	5.00	5.17	4.84
LJ FINALIST 6	5.56	4.17	5.77	4.05
LJ FINALIST 7	4.05	3.66	5.36	4.26
MEAN ± SD	4.68 ± 0.45	4.38 ± 0.52	5.31 ± 0.44	4.53 ± 0.52

Table 4.46. Step rate of the last 4 steps to the take-off board. *LJ Finalist = long jump finalist.*

Table 4.47 below shows the step width of the best individual jump of 7 finalists during their last 4 steps before the take-off board. The mean ± SD for step width for the fourth-last step was 0.10 ± 0.07 m, the third-last step was 0.13 ± 0.06 m, the second-last step was 0.16 ± 0.09 m, and the last step was 0.21 ± 0.10 m.

Athlete	4th-last step (m)	3rd-last step (m)	2nd-last step (m)	Last step (m)
LJ FINALIST 1	0.04	0.12	0.21	0.06
LJ FINALIST 2	0.11	0.22	0.06	0.28
LJ FINALIST 3	0.01	0.10	0.05	0.19
LJ FINALIST 4	0.14	0.19	0.30	0.37
LJ FINALIST 5	0.07	0.06	0.15	0.15
LJ FINALIST 6	0.21	0.06	0.20	0.25
LJ FINALIST 7	0.10	0.14	0.19	0.18
MEAN ± SD	0.10 ± 0.07	0.13 ± 0.06	0.16 ± 0.09	0.21 ± 0.10

Table 4.47. Step width of last 4 steps to the take-off board. *LJ Finalist = long jump finalist.*

Table 4.48 below shows the step width of 7 finalists for the last four steps and changes between those steps going into the take-off board. The mean ± SD for step width changes from the fourth-last to third-last step was 0.03 ± 0.09 m, the third-last to second-last step was 0.04 ± 0.11 m, and the second-last to last step was 0.05 ± 0.12 m.

Athlete	4^{th} last step (m)	3^{rd} last step (m)	2^{nd} last step (m)	Last step (m)	Δ 4^{th} – 3^{rd} last step (m)	Δ 3^{rd} – 2^{nd} last step (m)	Δ 2^{nd} – last step (m)
LJ FINALIST 1	0.04	0.12	0.21	0.06	0.08	0.09	-0.15
LJ FINALIST 2	0.11	0.22	0.06	0.28	0.11	-0.17	0.22
LJ FINALIST 3	0.01	0.10	0.05	0.19	0.08	-0.05	0.14
LJ FINALIST 4	0.14	0.19	0.30	0.37	0.05	0.11	0.08
LJ FINALIST 5	0.07	0.06	0.15	0.15	0.00	0.08	0.00
LJ FINALIST 6	0.21	0.06	0.20	0.25	-0.16	0.14	0.06
LJ FINALIST 7	0.10	0.14	0.19	0.18	0.05	0.05	-0.01
MEAN ± SD					0.03 ± 0.09	0.04 ± 0.11	0.05 ± 0.12

Table 4.48. Step width for the last four steps along with the change (Δ) between each step. (*Note: Positive values for change in step width indicate an increase between steps and negative values indicate a reduction in step width between steps*.)

Table 4.49 below shows the flight time of the best individual jump of 7 finalists during their last 4 steps before the take-off board. The mean ± SD for contact time for the fourth-last step was 0.110 ± 0.02 seconds, the third-last step was 0.123 ± 0.02 seconds, the second-last step was 0.080 ± 0.02 seconds, and the last step was 0.127 ± 0.03 seconds.

Athlete	4th last step (s)	3rd last step (s)	2nd last step (s)	Last step (s)
LJ FINALIST 1	0.113	0.093	0.120	0.080
LJ FINALIST 2	0.107	0.113	0.073	0.127
LJ FINALIST 3	0.107	0.147	0.073	0.133
LJ FINALIST 4	0.113	0.127	0.067	0.133
LJ FINALIST 5	0.107	0.127	0.073	0.100
LJ FINALIST 6	0.080	0.133	0.073	0.140
LJ FINALIST 7	0.140	0.120	0.080	0.173
MEAN ± SD	0.110 ± 0.02	0.123 ± 0.02	0.080 ± 0.02	0.127 ± 0.03

Table 4.49. Flight times of the last 4 steps to the take-off board. *LJ Finalist = long jump finalist.*

Table 4.50 below shows the contact time of the best individual jump of 7 finalists during their last 4 steps before the take-off board. The mean ± SD for contact time for the fourth-last step was 0.106 ± 0.005 seconds, the third-last step was 0.103 ± 0.01 seconds, the second-last step was 0.110 ± 0.01 seconds, and the last step was 0.102 ± 0.02 seconds.

Athlete	4th last step (s)	3rd last step (s)	2nd last step (s)	Last step (s)
LJ FINALIST 1	0.100	0.107	0.100	0.113
LJ FINALIST 2	0.113	0.107	0.107	0.107
LJ FINALIST 3	0.107	0.113	0.127	0.120
LJ FINALIST 4	0.107	0.100	0.107	0.060
LJ FINALIST 5	0.107	0.073	0.120	0.107
LJ FINALIST 6	0.100	0.107	0.100	0.107
LJ FINALIST 7	0.107	0.113	0.107	0.100
MEAN ± SD	0.106 ± 0.005	0.103 ± 0.01	0.110 ± 0.01	0.102 ± 0.02

Table 4.50. Contact times of the last 4 steps to the take-off board. *LJ Finalist = long jump finalist.*

Table 4.51 below shows the step time of the best individual jump of 7 finalists during their last 4 steps before the take-off board. The mean ± SD for contact time for the fourth-last step was 0.215 ± 0.02 seconds, the third-last step was 0.226 ± 0.02 seconds, the second-last step was 0.189 ± 0.02 seconds, and the last step was 0.229 ± 0.03 seconds.

Athlete	4th last step (s)	3rd last step (s)	2nd last step (s)	Last step (s)
LJ FINALIST 1	0.213	0.200	0.220	0.193
LJ FINALIST 2	0.220	0.220	0.180	0.234
LJ FINALIST 3	0.214	0.260	0.200	0.253
LJ FINALIST 4	0.220	0.227	0.173	0.193
LJ FINALIST 5	0.213	0.200	0.193	0.207
LJ FINALIST 6	0.180	0.240	0.173	0.247
LJ FINALIST 7	0.247	0.233	0.187	0.273
MEAN ± SD	0.215 ± 0.02	0.226 ± 0.02	0.189 ± 0.02	0.229 ± 0.03

Table 4.51. Step times of the last 4 steps to the take-off board. *LJ Finalist = long jump finalist.*

Figure 4.22 below displays the mean contact time and flight time of the best individual jump for the 7 finalists for the *fourth-last steps* before the take-off board. The mean ± SD was 0.106 ± 0.005 s (contact time) and 0.110 ± 0.02 s (flight time).

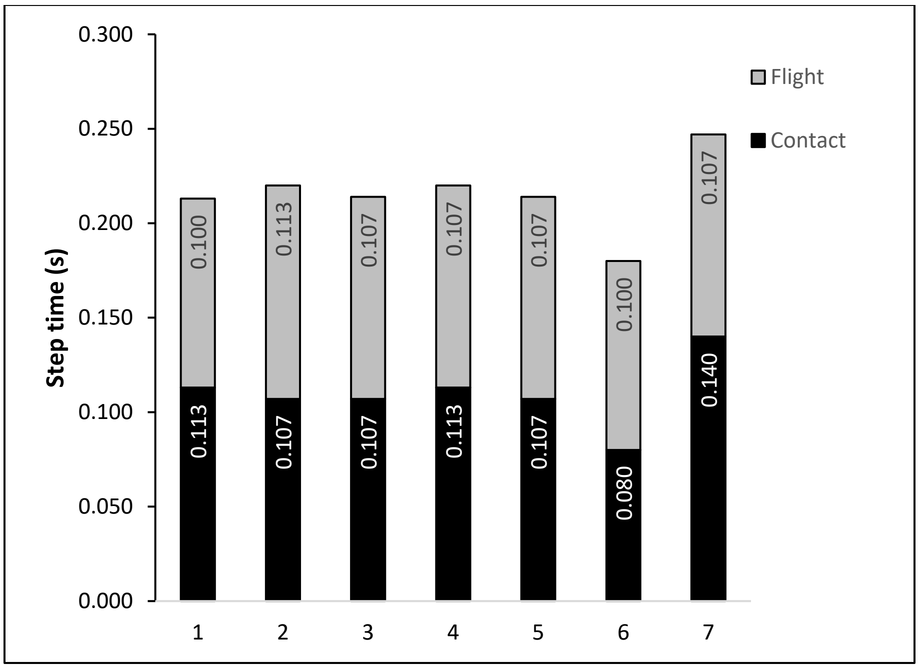


Figure 4.22. Contact and flight times for 7 finalists during the fourth-last step of the approach to the take-off board.

Figure 4.23 below displays the mean contact time and flight time of the best individual jump for the 7 finalists for the *third-last steps* before the take-off board. The mean ± SD was 0.103 ± 0.01 s (contact time) and 0.123 ± 0.02 s (flight time).

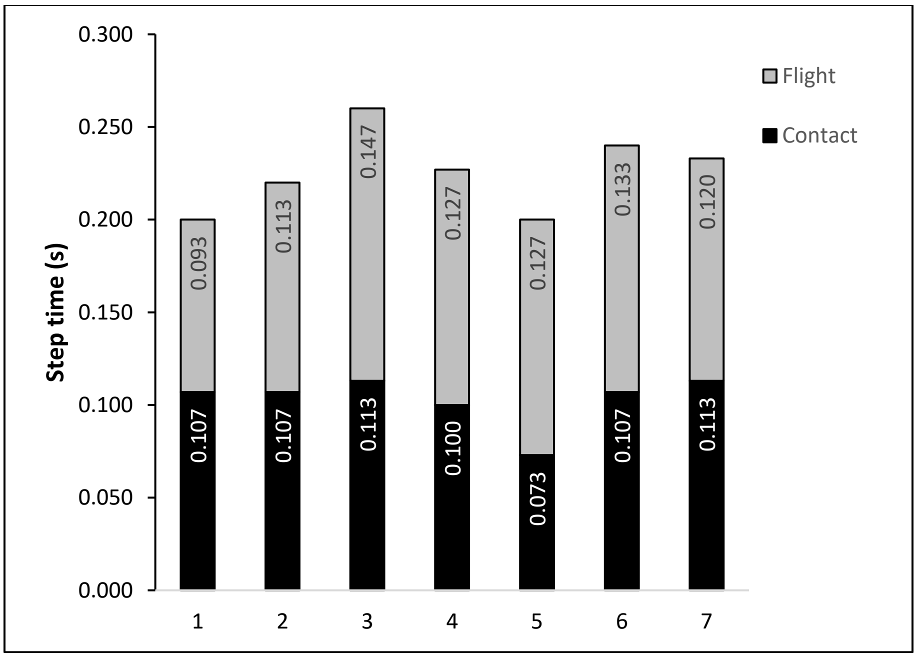


Figure 4.23. Contact and flight times for 7 finalists during the third-last step of the approach to the take-off board.

Figure 4.24 below displays the mean contact time and flight time of the best individual jump for the 7 finalists for the *second-last steps* before the take-off board. The mean ± SD was 0.110 ± 0.01 s (contact time) and 0.080 ± 0.02 s (flight time).

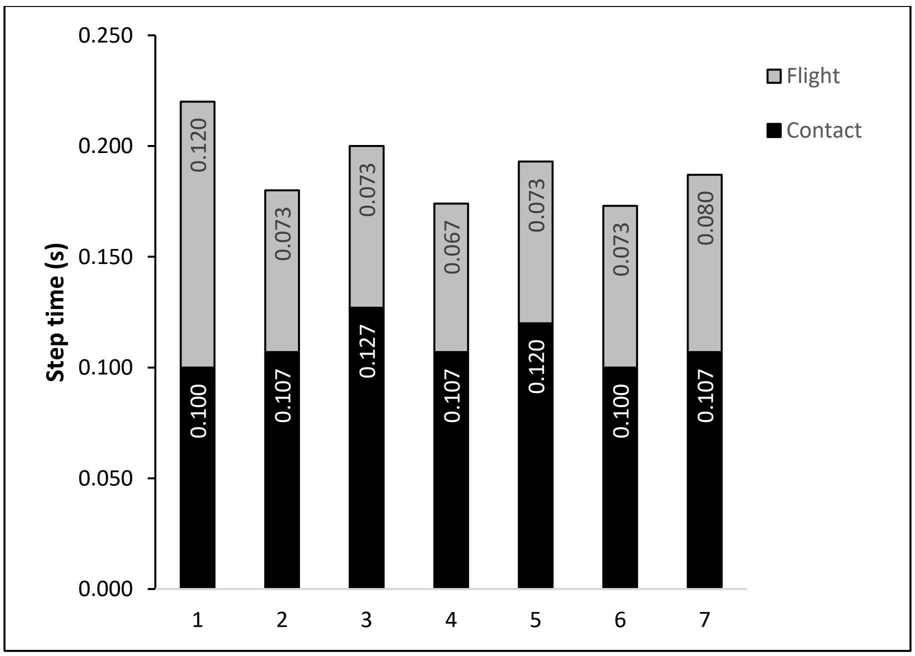


Figure 4.24. Contact and flight times for 7 finalists during the second-last step of the approach to the take-off board.

Figure 4.25 below displays the mean contact time and flight time of the best individual jump for the 7 finalists for the *last step* before the take-off board. The mean ± SD was 0.102 ± 0.02 s (contact time) and 0.127 ± 0.03 s (flight time).

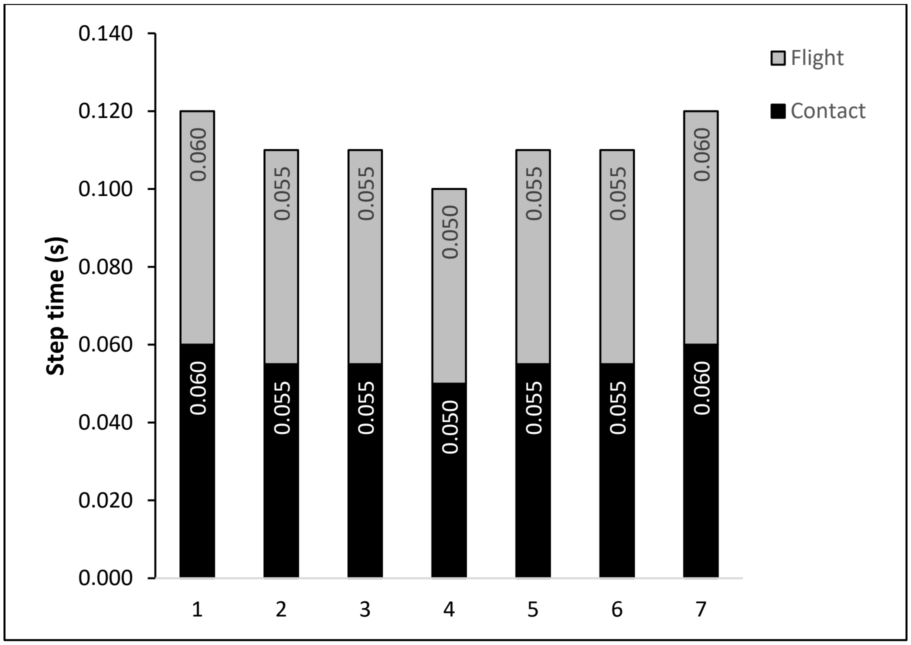
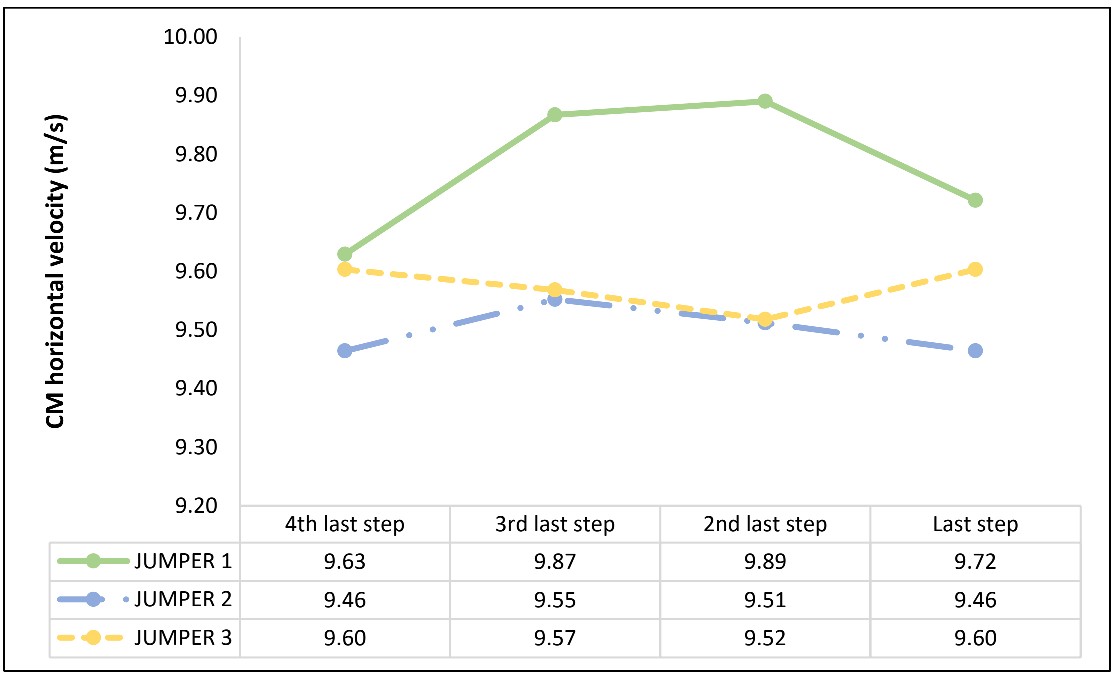


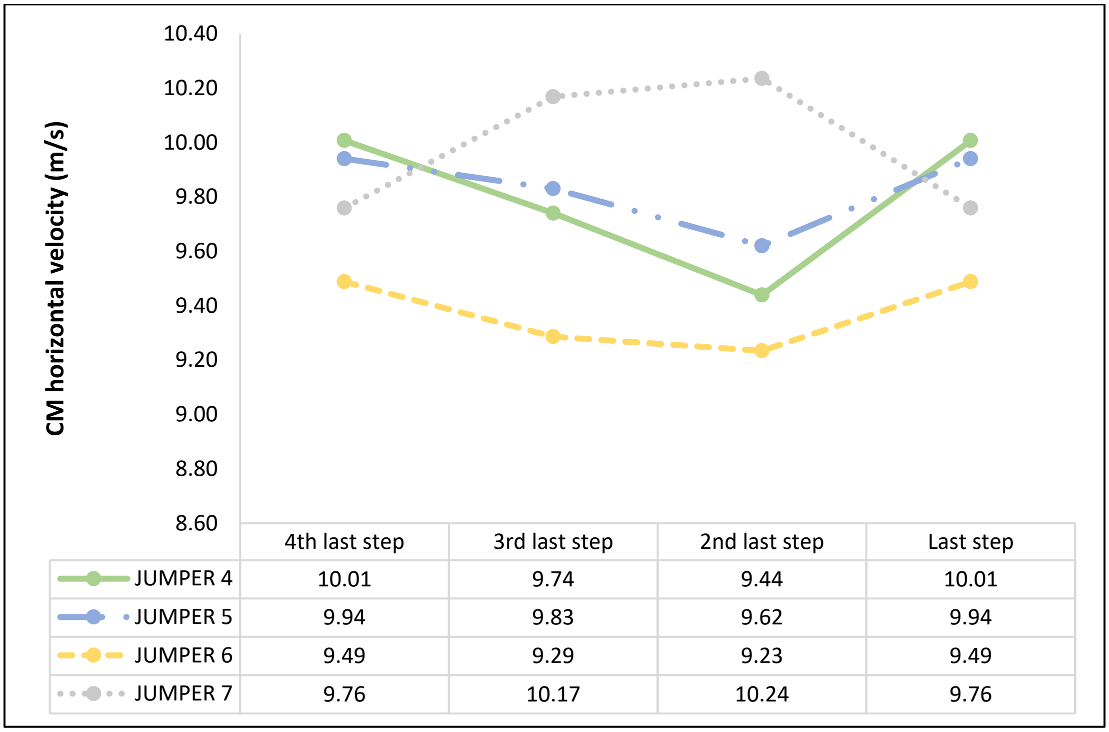
Figure 4.25. Contact and flight times for 7 finalists during the last step of the approach to the take-off board.

Figures 4.26 and 4.27 show the CM horizontal velocities for the last four steps for 7 finalists. The mean change in velocity from the fourth-last to the third-last step was a reduction of 0.002 m/s. The mean change in velocity from the third-last to the second-last step was a reduction of -0.008 m/s. The mean change in velocity from the second-last to the last step was a reduction of 0.009 m/s. Correlation between the official mark and CM horizontal velocity of the final steps were r = -0.62 (fourth-last), -0.26 (third-last), -0.07 (second-last), and -0.55 (last step).



	4th last step	3rd last step	2nd last step	Last step
JUMPER 1	9.63	9.87	9.89	9.72
JUMPER 2	9.46	9.55	9.51	9.46
JUMPER 3	9.60	9.57	9.52	9.60

Figure 4.26. Change in center of mass (CM) horizontal velocity during the last four approach steps for the *top 3 finalists.*



	4th last step	3rd last step	2nd last step	Last step
JUMPER 4	10.01	9.74	9.44	10.01
JUMPER 5	9.94	9.83	9.62	9.94
JUMPER 6	9.49	9.29	9.23	9.49
JUMPER 7	9.76	10.17	10.24	9.76

Figure 4.27. Change in center of mass (CM) velocity during the last four approach steps for the *next 4 finalists*.

Chapter 5
DISCUSSION

5.1 INTRODUCTION

This chapter discusses the results of the project and offers coaching commentary to provide perspective on championship performance in the 100-m and long jump. The study aimed to inform on the movements achieved during the highest collegiate Athletics competition available where coaches prepare and instruct athletes according to performance. The discussion will include a 100-m time analysis, long jump official mark analysis, and kinematic parameter analyses of each discipline.

Although general comparisons between sub-elite (college) and elite sprinter kinematic parameters could be made, it must be noted the NCAA championship and World championship competition qualifying structure is different. Championship format (order of disciplines and days contested on), the number of disciplines (e.g., relays) participated in, the amount of time between disciplines, and training loads must be considered. This project aimed to create and establish championship biomechanical analyses for future comparisons of collegiate performances, as it was done with the second-ever contested WC.

5.2 SPRINT DISCIPLINE – 100-M

In the Women's 100-m, determinants associated with specific sprint phases were identified and evaluated as likely decisive factors relating to performance outcomes. (*Note: All contested races were deemed to have adequate conditions for competition; location, track surface, and wind readings were noted but not factors included in this analysis*).

Time Analysis of First Round, Quarterfinals, and Semi-finals

As seen in past biomechanical reports, results from the first round, quarterfinals, and semifinals of the 100-m were reported in Tables 4.2, 4.3, 4.4, 4.5, and 4.6. The results provide coaches with: 1) the level of performance needed to advance to the next 100-m round apart from season ranking, 2) how performances compared to season and personal bests, and 3) what improvement trends or regressions in sprint performance may have occurred during the championship. The results also suggest refinements that may have or could have been made in the technical execution between competition rounds.

The first round had a mean sprint time of 11.44 s that included a high of 11.98 s and a low of 10.91 s. The first round also had mean sprint times with a small effect size of 0.38 between the West and East Regions. In the quarterfinal rounds of 24 competitors in each region, the mean sprint time was 11.39 s in the West Region and 11.29 s in the East Region, with the fastest overall posted time between the two regions at 10.89 s. To be among the top 24 competitors to advance to the semi-finals (top 12 from each region), the mean sprint time was 11.41 s with the fastest time being 11.03 s. The nine sprinters to advance to the final posted a mean time of 11.06 s, with 10.74 s as the fastest time of these championships.

Advancement from the first round to the quarterfinals of the 100-m was based on the top three times in each heat and the next six best times. The fastest of the automatic qualifying times was 10.91 s (West Region) and 11.01 s (East Region). The slowest of the next 6 best times posted were 11.42 s (West Region) and 11.50 s (East Region). There was a small effect size of 0.51 between quarterfinal mean sprint times between the West and East Region.

Advancement from quarterfinals to the 100-m semi-finals was based on the top three times in each heat and the next three best times. In the West Region, the slowest of the automatic qualifying times was 11.39 s with the fastest qualifying time at 10.89 s. In the East Region, the slowest of the automatic qualifying times was 11.31 s and the fastest qualifying time was 10.92 s. The next three best times posted were between 11.37 – 11.41 s (West Region) and 11.25 – 11.27 s (East Region).

Advancement from the semi-finals to the 100-m final was based on the top two in each heat and the next three best times. The fastest automatic qualifying time was 11.03 s whereas the slowest qualifying time was 11.30 s. In fact, five semi-finalists ran faster than the slowest qualifying time, leaving four semi-finalists running between 11.35 – 11.40 s. A very large effect size of 2.05 was found between the qualifiers and non-qualifier's mean sprint times posted in the semi-final rounds.

The advancement process through the NCAA Championships affirms the value of becoming an automatic qualifier (denoted as '*Q*') versus a non-automatic (qualifying by time) qualifier (denoted as '*q*') during the rounds. A sprinter who can achieve an automatic qualifying position to the next round suggests overall race speed was a dominant factor in performance outcomes. Finalists in the semi-final reached a mean velocity of 8.88 m/s followed by a mean of 9.07 m/s in the final. A mean improvement of 2% m/s in the rate of speed was seen by all finalists from the semi-final to the final.

Qualifiers attaining a non-automatic position, based on time through these championship rounds, revealed the ability of a sprinter to meet the minimum velocity needed to advance outside of the top position holders in their heat. This is an important finding that shows in a fast heat, a non-automatic qualifier who stays in reach or runs comparable velocities achieved by the automatic qualifiers still has an opportunity to advance to the next round. At times, non-automatic qualifiers run faster than automatic qualifiers. In this 2021 NCAA championship, three finalists ran faster than the last automatic qualifying position. Coaches should inform athletes to continue to execute their phases as instructed to reach high overall race speeds. Regardless of race position, athletes should focus on sprint mechanics and run through the finish line for the possibility to advance by time if they have not earned an automatic spot.

Sprint Finalists

Sub-section 4.2.2 provides more detailed information on the nine finalists. Figure 4.2 and Table 4.7 show graphical and table presentations of the progression each finalist took in terms of official times achieved leading into and including the final. The first round and final both had the largest standard deviation of 0.24 s. With the first round and quarterfinals contested in the same week two days apart, six finalists either repeated or improved their time in the quarterfinals with a mean and standard deviation of -0.05 ± 0.14 s. Going from the semi-finals to the finals contested 2 weeks later in the same week two days apart, every finalist ran faster in the final with a mean and standard deviation of -0.21 ± 0.14 s. Overall progress made from the first to the final round found finalists to improve by a mean and standard deviation of -0.08 ± 0.21 s. (*Note: Negative (-) sign indicates a drop (improvement) in time by seconds.*)

Based on the collegiate post-season championship schedule, it can be inferred that the days (up to 14) in between competition rounds provide coaches time to assess performance, tailor instruction, and modify training methods to produce the most optimal sprint techniques needed in competition. There is value in coaches exploring areas where subtle but intentional changes in sprint mechanics can be made to aid in running efficiency during competition. This notion reflects Mann (2015) who observed previously the merit in identifying sprint areas of interest, describing those positions of interest, and then examining the mechanics of those areas, all to better understand sprint performance.

Comparisons of the official final time, a season best, and personal best are shown in Table 4.8. Five finalists did not run faster than their season best in the final, while four finalists did. This suggests the four finalists that bolstered their season best may have properly applied modifications made in training to technical sprint components used in competition. Results also exhibited finalists peaking at the right time of the season.

Noted in past WC reports, the number of steps, relative to official race time, taken in the race by each finalist was reported in Table 4.9. Steps taken in this final ranged from 46 – 52 with a mean of 4.48 steps per second. The SR value represents the importance of attaining high running speed and the maintenance of that speed for overall performance. Coaches should infer that high-intensity races, like the 100-m, require the development and maintenance of an optimal SR an athlete can reach and hold. As energy becomes less available in a sprint race, the commitment of the athlete is needed to stay disciplined in the technical demands needed to sustain speed for as long as possible. Tellez' (2014) description of sprinting momentum being built until its peak is reached and maintained to decelerate as little as possible, confirms the importance of high running speed. Although many other considerations (e.g., participation in other disciplines (race load), weather, wind, etc.) may have influenced final race results seen in Table 4.8 and 4.9, it is important to explore further key determinants that have been associated with the phases of sprint performance.

Reaction Time

Reaction times have been presented in past literature to determine its significance in competition results. As seen in Table 4.11, a comparison of the reaction times found the final winner had the fastest (0.124 s) while the ninth finalist had the second best (0.137 s). The highest reaction time (0.200 s) paired with a fifth-place finish. Four of the finalists were above the mean reaction time with five finalists were below the mean reaction time of 0.166 s. The mean sprint time of finalists above the mean reaction time was 11.17 s whereas the mean sprint time of finalists below the mean reaction time was 10.98 s (range of 10.79 – 11.22 s). The correlation between reaction time and final performance results was $r = -0.22$. Excluding the winner of the 100-m final, the reaction times did not correspond to the race results in terms of the race finish. A trivial effect size of 0.20 was found between reaction times achieved in the semi-final versus the final for the nine finalists.

While some finalists had achieved a better reaction time in the semi-finals seen in Table 4.10, they were not able to produce the same or a better reaction time in the final. Interestingly, all finalists ran faster in the final than in the semi-final irrespective of their reaction time.

Time Analysis of 100-m Final

An in-depth look at race results found four finalists ran faster than their season and personal best times in the final with three of those finalists running sub-11 seconds. One finalist ran only 0.01 s off their season and personal best time. A trivial effect size of 0.10 and 0.05 was found between the finalists' final time and season best, and the finalists' final time and personal best, respectively.

Contested over two days—semi-final on Thursday and final on Saturday—all finalists ran faster in the final than the semi-final. Interestingly, the four finalists with a sub-11 second official time took 49 or 50 steps (10.74 s, 49 steps; 10.79 s, 50 steps; 10.90 s, 50 steps; 10.88 s, 50 steps) in the race. Steps per second for the four sub-11 s finalists were 4.56, 4.63, 4.59, and 4.60 steps per second. This suggests step length (SL) and the rate at which steps were taken during the race likely influenced performance outcomes.

Table 4.12 showed velocities achieved during the entire semi-final and final race. A moderate effect size of 1.12 was found between the semi-final and final velocities of the finalists. All finalists ran faster velocities in the final with a mean increase of 2%. This suggests finalists made improvements in one or more phases during the race. Table 4.13 shows how four phases were evaluated in this final: 0 – 30-m (acceleration), 30 – 60-m (maximal velocity), 60 – 100-m (maintenance and deceleration), and 0 – 100-m (full race). Velocities were calculated using the distance of each phase and the speed achieved within those phases. Velocities reached were most similar among finalists within the acceleration phase (range of 7.25 – 7.49 m/s) and largely dissimilar within the deceleration phase (range of 9.34 – 10.21 m/s). It can be inferred that finalists may share commonalities in kinematic parameter values during acceleration but differ in deceleration. Variance in velocities heading to the deceleration phase may have been a result of a breakdown in sprint mechanics where running form was not held well after maximal velocity was reached.

Table 4.14 lists the speed time each finalist ran during acceleration (0 – 30-m), maximal velocity (30 – 60-m), maintenance and deceleration (60 – 100-m), and the full race (0 – 100-m). Finalists who were able to achieve an acceleration of 4.10 s or better corresponded to a maximal velocity of 2.90 s or faster. It can be inferred that the top four finalists had a greater acceleration ability and transfer of speed to their maximal velocity phase. This suggests the combination of acceleration and maximal velocity times achieved may have decided the Women's 100-m final.

Times posted through all qualifying rounds show the range of participating competitors among the top sprinters at the NCAA level. In the three rounds needed to become a finalist, coaches must consider how training is transferring to competition and what technical components are ideal to achieve sprint times at the highest level.

Acceleration Phase

Within the calibrated acceleration phase (13 – 20-m), noteworthy differences between finalists were found in several parameters. All finalists had a total of two right and two left foot contacts within the 13 – 20-m except finalist 8 (two right and one left foot contact). As an area of interest for coaches, a sub-phase (first sub-phase, 13 – 16.5-m; second sub-phase, 16.5 – 20-m) analysis was done to further describe the acceleration phase. Each sub-phase included up to four steps, or rather, up to four-foot strikes within the phase.

For the entire acceleration phase (Table 4.15), the greatest variance between finalists was found in step rate (SR) covering a range of 4.44 – 5.07 Hz whereas step length (SL) had only a difference of 0.06 m in a range from 1.82 – 2.03 m. The four sub-11 s finalists had a SR and SL pair of 4.82 Hz and 1.95 m (finalist 3, 10.92 s); 4.99 Hz and 1.93 m (finalist 5, 10.89 s); 5.00 Hz and 1.92 m (finalist 6, 10.91 s); and 4.94 Hz and 1.90 m (finalist 7, 10.87 s). This suggests the reliance on either SR or SL is individualized in competition for not only top-level elite sprinters but also applies to top-level collegiate sprinters, supporting Salo et al. (2011) findings. Salo et al. (2011) mentioned Luhtanen and Komi being among the first to present findings on SR and SL but noting their study did not reflect elite sprinters (Salo et al., 2011). In another study, Hunter et al. (2004) stated that group-level SL was significantly related to running velocity for longer periods of time whereas SL was not more of a factor in the short term (Hunter, et al., 2004; Salo et al., 2011). With such studies identifying only SR or SL as a main reason for faster running velocities, Salo et al. (2011) study pointedly assessed step characteristics of elite athletes individually and longitudinally across multiple competitive races (Salo et al., 2011). Hence, the evaluation of SR and SL in this project highlights the reliance variability of both parameters during acceleration on those considered sub-elite but performing at an elite level.

Other variables measured during the entire acceleration phase included contact time, flight time, and step time listed in Figure 4.3. The five sub-11 s finalists had either a longer contact time, flight time, or both. A contact time of 0.105 s or greater and a flight time of 0.096 s or greater demonstrated official race times of 11 s. Sub-11 s finalists had a contact time of 0.105 s or less and a flight time of 0.110 s or less. Two outliers included finalist 3 (0.098 s contact time; 0.110 s flight time) and finalist 2 (0.116 s contact time, 0.110 s flight time). These results support Murata et al. (2018) findings of higher SR from the 9th to 20th step existing during the middle and later acceleration phase mentioned in Chapter 3 (sub-section 2.5.1.1).

Specific velocities were calculated for the entire calibrated acceleration phase. As noted in the results section (Table 4.16 and Figure 4.4), notable differences between step velocity and CM horizontal velocity were found for finalists 4, 5, 6, and 7. Step velocity and CM horizontal velocity was closest in value for finalist 2 while the biggest difference in value was seen in finalist 4. Specifically, CM horizontal velocity for right-left and left-right steps were similar among finalists except for finalist 4 as the dominant outlier at 7.87 m/s on the right-left step and 9.07 m/s on the left-right step. This suggests the acceleration development of each finalist and management of velocity based on step-to-step changes caused a shift in the CM position in the horizontal direction. Nagahara et al. (2014) found that measured spatiotemporal and kinematic variables indicated step-to-step changes during steps 4 to 14 in the acceleration phase. Between these two velocities, a moderate effect size of 0.96 was found.

The swing time among finalists in the entire acceleration phase showed a mean of 0.311 ± 0.02 s (Figure 4.5). Finalist 4 had the shortest swing time of 0.291 s while finalist 1 had the longest swing time of 0.334 s. Although the swing phase is typically evaluated during high horizontal velocity, the swing time during acceleration suggests how mechanically effective a sprinter is during acceleration. It can be inferred that an under-developed acceleration phase may lead a sprinter to have a longer horizontal velocity swing time due to being in early maximal velocity running mechanics.

Related to acceleration, DCM TD (distance CM perpendicular to the running surface at touchdown) and DCM TO (distance CM perpendicular to the running surface at toe-off) for left and right foot contacts were reported in Tables 4.17 and 4.18. There was a moderate effect size of 0.75 between the left and right foot contacts for DCM TD and a small effect size of 0.25 for DCM TO. On touchdown, CM distance for both foot contacts were at or above 0.25 m for all finalists except finalist 7 at 0.23 m. CM distance for both foot contacts at take-off was above 0.65 m for all finalists except finalists 1 and 3. These results suggest the foot placement each finalist took relative to their CM and support phases during acceleration.

Morin et al. (2011) describe accelerated phase runs encompassing support phases consisting of braking phases (negative horizontal GRF) followed by propulsive phases (positive horizontal GRF). Finalists 3, 4, 6, and 9 were within 0.03 m or less between the left and right foot contacts for DCM TD. Finalists 1, 2, 3, 5, 7, and 8 were within 0.02 m or less between the left and right foot contacts for DCM TO. This suggests these finalists were able to limit the percentage of the braking phase at touchdown and optimize the percentage of the propulsive phase at toe-off to create effective accelerative steps.

In summary, the rate at which steps are taken, ground time during each step, and flight time between steps, reflect the efficiency at which movement is made during acceleration. It can be inferred that the more efficient an athlete's acceleration is, the more effective they will be in the steps taken during acceleration, which serves as the required precursor to the next phase of sprint running. Coaches should consider assessing acceleration from an individual perspective and in sub-phases to know where a lack of efficiency may exist.

Acceleration Sub-Phases

As presented in Chapter 3 (sub-section 2.5.1.1), evaluating acceleration in sub-phases is reasonable by scientists and coaches. In the first sub-acceleration zone (13 – 16.5-m), Table 4.19 shows the SR range was as low as 4.42 Hz and as high as 5.01 Hz while the SL range was 1.87 to 2.00 m. Outliers included finalist 2 (4.42 Hz and 2.00 m), finalist 4 (5.01 Hz and 1.81 m), and finalist 7 (5.01 Hz and 1.87 m). The SL distances reflect and are dependent on body height and leg length, as mentioned by Čoh et al. (2001) and Mann (2015). Step width is also shown in both phases with a range of 0.08 to 0.24 m for the first sub-phase and 0.04 to 0.29 m for the second sub-phase. Within these three parameters, a small (0.50) effect size for SL, and a trivial, 0.05 and 0.14, effect size for SR and SW were found between the two sub-phases.

In comparison to the first sub-phase, Table 4.20 shows the second sub-phase

(16.5 – 20-m) SR ranges being as low as 4.45 Hz and as high as 5.13 Hz while the SL ranges from 1.84 to 2.06 m. Outliers in this sub-acceleration included finalist 4 (5.13 Hz and 1.93 m), finalist 5 (5.07 Hz and 1.90 m), and finalist 7 (4.88 Hz and 2.06 m). Although this sub-phase is within the same acceleration, changes within SR and SL were significant within and between finalists. Among outliers mentioned in both sub-phases, going from the first sub-phase to the second sub-phase,

- Finalist 2 – SL remained around the same length, but SR increased in frequency by 3.3%.
- Finalist 3 – SL remained around the same length, but SR reduced in frequency by 2.6%.
- Finalist 4 – SL remained around the same length and SR remained around the same frequency.
- Finalist 6 – SL remained around the same length, but SR increased in frequency by 2.4%.
- Finalist 7 – SL increased in length by 2.7%, but SR remained around the same frequency.

An increase in SL paired with a reduced SR suggests specific finalists begin to cover more distance at the expense of a reduced SR, thus were unable to maintain their frequency levels upon lengthening step distances. An increase in SL paired with an increase in SR suggests specific finalists begin to cover more distance in each step without compromising the rate at which those steps were taken, thus showing an ability to cover more ground at a faster rate. It can be inferred that finalists with a greater SL at the 8th step (initial acceleration) and a higher SR from the 9^{th} to 20^{th} step (middle and later acceleration) were most effective during their acceleration based on Murata et al. (2018) findings.

The relationship between SR and SL were displayed as sprint velocities in Figures 4.6 and 4.7 for each sub-acceleration zone. In comparison, it was tenable to see the second sub-phase have a faster mean than the first sub-phase, 9.38 $m \cdot s^{-1}$ versus 9.16 $m \cdot s^{-1}$. Sprint velocity improvements from one sub-phase to the next suggest an ability of the finalists to develop their acceleration from sub-phase to sub-phase by creating forces where their CM projects forward during acceleration. This reflects transitions being made within the acceleration phase (Nagahara et al., 2014a; Nagahara et al., 2020).

Acceleration Center of Mass

In Figures 4.8 and 4.9, overall step time (sum of contact time and flight time) between the sub-phases were very similar in mean and standard deviation. A moderate effect size of 1.00 was found for both contact and flight times, with a trivial effect size of 0.00 for step time having the exact mean and standard deviation of 0.21 ± 0.01 for both phases.

Specifically, an assessment of flight time found finalists 2 and 5 were the largest outliers between their left and right foot contacts in the first sub-phase. Finalist 2 had a difference of 0.20 s while finalist 5 had a difference of 0.25 s. In the second sub-phase, finalist 8 had the largest difference of 0.25 s among all finalists. Flight times of these three finalists suggest an increase or decrease in SL and SR in select acceleration sub-phases. Agreeing with previous findings from Hunter et al. (2004) and Nagahara et al.

(2014), an increase in flight time stems from an increase in SL whereas a small increase in flight time was needed to maintain SR. Therefore, the importance of length or rate in the steps taken varied for each finalist to meet the demands of each acceleration sub-phase. Value exists in coaches determining when and where SL and SR are most important for an athlete to have effective accelerative efforts. This establishes the likelihood other key components of acceleration can develop based on SL and SR being addressed early on in sprint performance.

Such components include types of velocity. Differences in step velocity and CM horizontal velocity between the sub-phases were found (Tables 4.21 and 4.22; Figure 4.10 and 4.11). There were four finalists with a difference above 0.30 m/s in step velocity and five finalists with a difference above 0.50 m/s in CM horizontal velocity. Specifically for CM horizontal velocity, the mean and standard deviation values were similar between the left-to-right step (9.07 ± 0.19 m/s) and the right-to-left step (9.11 ± 0.29 m/s) for the first sub-acceleration phase. Finalist 4 was the outlier in the first sub-phase with a left-to-right step at 8.86 m/s and a right-to-left step at 6.50 m/s. In the second sub-acceleration phase, finalist 1 was the outlier in having CM horizontal velocity for both left-to-right and right-to-left steps under 9.00 m/s while all other finalists achieved over 9.00 m/s for both steps. These velocities may suggest the ability each finalist had in applying forces in the horizontal direction passing through their CM to generate the fastest possible acceleration within each sub-phase, a notion supported by Bezodis et al. (2021) (sub-section 2.5.1.1). Step velocity between sub-phases had a small effect size (0.56) while CM horizontal velocity had a large effect size, 1.33.

In further assessing each sub-phase, swing time was reported in Figures 4.12 and 4.13. The effect size was trivial at a value of 0.05 between the two sub-phases. Defined as the amount of time the foot is not in full contact with the ground in one complete stride (section 3.9), swing time ranges of 0.290 – 0.335 s with less than 0.02 s difference between the two phases were found. Among finalists, the difference between each sub-phase included: the same amount of time (two finalists), the difference between 0.000 – 0.049 s (four finalists), and the difference at or above 0.005 s (three finalists).

Additionally, DCM TD (distance CM perpendicular to the running surface at touchdown) and DCM TO (distance CM perpendicular to the running surface at toe-off) were measured in each sub-phase and shown in Tables 4.23 and 4.24. The largest differences were found in the first sub-phase for DCM TD for finalist 2 (0.11 m), finalist 5 (0.14 m), and finalist 8 (0.09 m); and for DCM TO for finalist 7 (0.05 m), both finalist 4 and 6 (0.04 m). The second sub-phase for DCM TD showed the largest differences for finalist 1 (0.07 m) and finalist 5 (0.10 m) while DCM TO values were largest for finalist 4 (0.04 m) and finalist 6 (0.05 m).

The swing time, DCM TD, and DCM TO distance achieved during these sub-phases show the dynamic behavior of sprinting during acceleration by the finalists. The results suggest kinematic changes occurring due to the balance of force and motions made by each finalist during the acceleration phase. To optimize their sprint performance, finalists appeared to transition within the acceleration sub-phases by absorbing changes made individually in SL, SR, CM, and foot contact. Hunter et al. (2005), Cicacci et al. (2010), and Morin et al. (2011) support the argument of strong variability existing in accelerative steps taken by sprinters when forward motion is generated. Therefore, coaches are advised to focus on foot placement in steps taken during acceleration, the rate at which steps are taken, and how sprinters transition from one step to the next heading towards maximal velocity. These measures may allow sprinters to meet more optimal technical efficiency during acceleration.

Asymmetry in Acceleration

For the purposes of this project, perfectly symmetrical represent values closer to 0% whereas perfectly asymmetrical represent values closer to 100% (Bissas et al., 2022). The entire acceleration, as one phase, results revealed some variability between left and right foot contacts for select kinematic parameters suggesting functional asymmetries. Three parameters were assessed for asymmetry with the acceleration phase: CM horizontal velocity, DCM TD, and DCM TO.

Figure 4.4 shows CM horizontal velocities for left-right and right-left contacts. Four finalists had more than a 0.30 m/s difference between foot contacts. Specifically, finalist 4 was the dominant outlier at 7.87 m/s on the right-left step and 9.07 m/s on the left-right step with a difference of 1.20 m/s between foot contacts. Although these velocities were important to note between left and right foot contacts, asymmetry percent differences were worthy to note as well. Four finalists were at or above 1.2% while 5 finalists were under 1.0%.

DCM TD and DCM TO parameters also reported left and right contact values that exhibited possible asymmetry (Table 4.17). For DCM TD, three finalists had more than a 0.05 m difference between their left and right foot contacts, while three finalists had a 0.04 m difference between their left and right foot contacts. Asymmetrical percentage differences for DCM TD were as low as 0.6% (finalist 3) and as high as 14.5% (finalist 5). For DCM TO, finalists 4 and 9 had a difference of 0.04 m while all other finalists were 0.03 m or less. The asymmetrical percentage differences for DCM TO were all under 2.0% for all finalists. Interestingly, finalist 3 had the same asymmetry percentage for DCM TD and DCM TO.

These results suggest the relationship between these kinematic parameters and asymmetry in the acceleration phase of sprinting is based on dynamic lower limb strength and dominant leg placement. Vagenas and Hoshizaki (1986) found sprinters exhibit a significant dynamic leg strength asymmetry showing a possible interaction between the force exerted by a sprinter and the duration of application of this force. In this 100-m final, the application of force by the dominant leg of finalists may be attributed to differences in CM horizontal velocity and horizontal distances achieved at touchdown and toe-off in steps taken during acceleration. Overall, all three parameters—CM horizontal velocity, DCM TD, and DCM TO—asymmetry percentages suggest finalists were able to express functional asymmetry between both limbs. Coaches should consider how the distribution, application, and placement of forces develop in each step taken during the early and middle steps of acceleration. This ultimately dictates how a sprinter moves through acceleration in preparation for maximal velocity.

Maximal Velocity Phase

Although practice environments may aim to simulate top-end speeds in training, maximal velocity in competition cannot be fully replicated. As an area of interest for coaches to consider, maximal velocity for the Women's 100-m final was evaluated. Within the selected maximal velocity phase (40 – 47-m) captured, noteworthy differences between finalists were found in several parameters.

Sub-section 4.2.2.2 reported the mean and standard deviation of kinematic characteristics—step length (SL), step rate (SR), and step width (SW)—in maximal velocity. Table 4.25 showed finalists reached a SL high of 2.28 m and a low of 2.03 m. The SR range was between 4.46 – 5.01 Hz with SW ranging between 0.07 – 0.23 m. Outliers included finalist 1 having the highest SL of 2.28 m paired with a SR of 4.94 Hz and SW of 0.20 m; finalist 7 with a SL of 2.26 m, SR of 4.46 Hz, and SW of 0.07 m; and finalist 8 with a SL of 2.03 m, SR of 5.01 Hz, and SW of 0.15 m. Of the four sub-11 s finalists, the mean and standard deviation for SL, SR, and SW was 2.17 ± 0.07 m, 4.89 ± 0.06 Hz, and 0.12 ± 0.03 m, respectively. These results suggest a reasonable SL or SR was reached and managed by each finalist during maximal velocity. Additionally, the results are supported by Salo et al. (2011) and Wild et al. (2022) statements on SR or SL being highly individual in the 100-m with no single optimal strategy existing during sprinting (sub-section 2.5.1.3).

With SL, SR, and SW results in mind, past studies have postulated the interaction of kinematic parameters and their influence on final performance outcomes. Structurally created by Hay, Paradisis and Cooke (2001) hierarchical model illustrates the possible contribution kinematic parameters have on running speed. Correlations were calculated between the finalists' official race times and select kinematic parameters in this project. The correlation between the final race time and SL was $r = -0.24$; final race time and SR was $r = -0.39$; and final race time and SW was $r = 0.02$. Although these step-characteristic kinematic parameters are contributing factors to high-level sprinting, the minimal correlations suggest no one parameter was a dominant factor relating to performance times posted.

The 30-m Fly

Figure 4.14 displays sprint velocity as a product of SR and SL interacting with each other. Tables 4.12 and 13 in sub-section 4.2.2 showed the mean and standard deviation of the entire race (0 – 100-m) to be 9.07 ± 0.19 m/s and 10.37 ± 0.23 m/s for the maximal velocity phase (30 – 60-m). Coaches have often referred to, in part or whole, the maximal velocity phase as the competition 30-m fly. Projected competition 30-m fly times are derived from practice test runs taken during training in which a 30-m segment is timed within a short sprint.

For example, equivalent projected training 30-m fly, competition 30-m fly, and 100-m race times have been listed below:

Athlete	Training 30-m fly (s)	Competition 30-m fly (s)	100-m Race Time (s)
RANGE 1	2.95 – 2.97	2.83 – 2.85	10.67 – 10.74
RANGE 2	2.98 – 3.00	2.86 – 2.88	10.77 – 10.84
RANGE 3	3.01 – 3.03	2.89 – 2.91	10.87 – 10.94
RANGE 4	3.04 – 3.06	2.92 – 2.94	10.91 – 11.04
RANGE 5	3.07 – 3.09	2.95 – 2.97	11.07 – 11.14
RANGE 6	3.10 – 3.12	2.98 – 3.00	11.17 – 11.24
RANGE 7	3.13 – 3.15	3.01 – 3.03	11.27 – 11.34

Table 5.1. Equivalent training 30-m fly, competition 30-m fly, and 100-m race time (*USATF, 2003*).

Finalists achieved a competition 30-m fly mean and standard deviation of 2.90 ± 0.06 s. Finalists 1 (2.97 s), 2 (2.99 s), and 9 (2.97 s) were the highest in the field. Competition 30-m fly times suggest comparable race sprint times an athlete could run if a 30-m fly was reached. Projected race time ranges given assume all things being equal (e.g., ideal race conditions, reaction time, acceleration, maintenance of sprint mechanics) will be met by the athlete.

The correlation between the final race time and competition 30-m fly for all finalists was $r = 0.89$. For the four sub-11 s finalists, the correlation between their final race time and competition 30m fly was $r = 0.75$. This suggests finalists may have reached a portion or most of their maximal velocity predicated on an optimal SL and SR developed during acceleration and transferred into running speed maintained as long as possible. This notion reflects Maćkała et al. (2015) reporting maximum speed for top-level sprinters is predicated on the sufficient length and optimum running speed during the acceleration phase (sub-section 2.5.1.3).

Speed Profiles

As measured in the acceleration phase, step time (sum of contact time and flight time), step velocity, and CM horizontal velocity were also measured for the maximal velocity phase. Figure 4.15 shows step time values for the left and right leg of each finalist. Assessing the step time as two separate components, the contact time between the left and right legs among all finalists ranged from 0.000 – 0.015 s. Flight time between left and right legs ranged from 0.000 – 0.025 s with five finalists equal to or less than 0.015 s and four finalists above 0.015 s.

Table 4.26 lists the step and CM horizontal velocities reaching during the maximal velocity phase. The effect size between these two parameters was trivial at 0.14. Step velocity was derived from step time and SL while CM horizontal velocity was derived from full-body digitization and is considered the most accurate (Bissas et al., 2018a; Bissas et al., 2018b). Finalists were able to reach over 10.00 m/s for both parameters, excluding finalist 1 achieving 9.95 m/s in step velocity and 9.91 m/s CM horizontal velocity, and finalist 2 reaching a 9.99 m/s CM horizontal velocity. Figure 4.16 revealed the largest differences in CM horizontal velocity between the left-right step versus right-left step were found for finalist 3 (11.16 m/s, left-right; 10.95 m/s, right-left) and finalist 6 (10.37 m/s, left-right; 10.55 m/s, right-left). All other finalists achieved velocities of 0.13 m/s or less between both steps. It can be inferred that 7 of 9 finalists had effective ground contact efforts on both left-right and right-left steps.

Interestingly, the correlation between the final race time and step velocity was r = -0.67 and -0.75 between the final race time and CM horizontal velocity. A high correlation was found between these velocities and final race performance times indicating these velocities provide another shell to the type of speed finalists were able to reach in this phase of the race. Bissas et al. (2018a) and Bissas et al. (2018b) velocity calculations (e.g., mean speed, step velocity, CM horizontal velocity) were given to form a complete view of speed profiles of sprint competitors. Attaining speed profiles may aid coaches in understanding how their athletes are creating and using speed during specific sprint phases.

Interestingly, the correlation between the final race time and step velocity was r = 0.31 and 0.27 between the final race time and CM horizontal velocity. Although a high correlation was not found between these velocities and final race performance times, these velocities provide another shell to the type of speed finalists were able to reach in this phase of the race. Bissas et al. (2018a) and Bissas et al. (2018b) velocity calculations (e.g., mean speed, step velocity, CM horizontal velocity) were given to form a complete view of speed profiles of sprint competitors. Attaining speed profiles may aid coaches in understanding how their athletes are creating and using speed during specific sprint phases.

With an understanding of force generation and efficient ground contact, the support and swing phases are also critical to the mechanics of sprinting during maximal velocity. Swing times shown in Figure 4.17 are of one complete stride (two steps) during the maximal velocity phase. Five finalists were at a mean of 0.310 while 5 finalists were above the mean. The values below the mean suggest those finalists may not have been able to maintain trunk and pelvic positions to reach a knee lift high enough during the swing phase. As a result, the swing phase was shortened with respect to time. The values above the mean may reflect finalists' reaching high knee lift positions during the swing phase with an ability to subsequently punch the same swing leg into the ground during this sprint phase. Thus, as a result, finalists were likely to have reduced their support duration, reduced their touchdown distance, and had a high overall leg stiffness during maximal sprinting (Mendiguchia et al., 2022; Clark et al., 2017; Clark & Weyand, 2014). Furthermore, swing times of finalists indicate the degree horizontal velocity of CM during maximal sprinting has been preserved. The concept of the swing leg and preservation of horizontal velocity of CM was found to be associated in an international 100-m competition of elite athletes where horizontal positioning of the foot was close to the CM at ground contact, high vertical ground reaction forces were generated, and minimal vertical displacement of the CM was made (Lehmann & Voss, 1997; Čoh et al., 2018).

Center of Mass at Touchdown and Toe-off

DCM TD (distance CM perpendicular to the running surface at touchdown), DCM TO (distance CM perpendicular to the running surface at toe-off), and CM contact distance (distance CM travels during single ground contact) were also measured during the maximal velocity phase (Tables 4.27 and 4.28). A small effect size of 0.20 was found for DCM TD and 0.35 for DCM TO between left and right foot contact. Finalists ranged between 0.26 – 0.35 m on DCM TD (left) and 0.28 – 0.35 m on DCM TD (right). DCM TO ranges for left and right were 0.59 – 0.70 m and 0.57 – 0.78 m, respectively. Sub-11 s finalists had a mean and standard deviation of 0.30 ± 0.03 m (DCM TD left), 0.36 ± 0.07 m (DCM TD right), 0.64 ± 0.03 m (DCM TO left), and 0.67 ± 0.07 m (DCM TO right).

Table 4.28 displays CM contact distance with six finalists having their CM travel under 1.00 m on their left and four finalists under 1.00 m on their right. There was a moderate effect size of 0.82 between the CM contact distance between left and right foot contacts. These results may suggest how efficiently finalists employed the use of 'front side’ mechanics versus ‘back side’ mechanics during maximal velocity. ‘Front side’ sprint mechanics promotes the body’s segments to be in front of the CM to establish effective ground contact to create the highest velocities possible (Mann, 2015).

Other measured kinematic parameters associated with CM included foot horizontal (Table 4.29) and vertical (Table 4.30) velocity pre-touchdown (TD) and at touchdown (TD). Effect sizes for pre-TD and TDs between left and right foot contacts were at: moderate, 0.70 (horizontal velocity pre-TD); moderate, 0.68 (horizontal velocity TD); small, 0.40 (vertical velocity pre-TD); and small, 0.49 (vertical velocity TD). Evaluating the mean values of the foot horizontal velocities for the left and right foot found four finalists above 3.40 m/s (at pre-TD) and the same four finalists above 2.50 m/s (at TD). For mean foot vertical velocity for the left and right foot, four finalists were between -2.80 and -3.00 m/s (at pre-TD), and all finalists except one were between -2.24 and -2.68 m/s (at TD). These velocities suggest characteristics of maximal velocity related to SR and SL based on how the elements of rapid ground contact and force application were made. The quality of both elements is dependent on the entire step cycle (Seagrave, 2009). Coaches must assess the step cycle as a whole and in parts to see where modifications in sprint mechanics can improve.

Postural Characteristics

Key joint angles at touchdown were measured and reported for each finalist in Tables 4.31, 4.32, and 4.33. Based on finalists (3, 5, 6, and 7) who ran sub-11 s, trunk, hip, knee, and ankle angles were dually noted.

	FINALIST 3		FINALIST 5		FINALIST 6		FINALIST 7	
Joint Angle	**Left (°)**	**Right (°)**	**Left (°)**	**Right (°)**	**Left (°)**	**Right (°)**	**Left (°)**	**Right (°)**
Trunk (α)	83.3	69.5	-	-	-	-	77.4	80.3
Hip (γ)	158.9	125.2	142.8	131.4	142.9	126.0	154.2	143.1
Knee (β)	152.9	134.3	142.1	131.3	157.1	141.3	159.3	150.3
Ankle (ι)	114.4	-	106.1	99.1	111.6	97.6	111.6	124.0

Table 5.2. Comparison of four angles between sub-11 second finalists on *touchdown* during maximal velocity phase. (*Note: Dash, '-', represents an angle value that was impossible to obtain due to technical limitation.*)

Among the sub-11 s finalists, trunk angles were between 69.0° and 84.0°; hip angles between 143.0° and 156.0°; knee angles between 125.0° and 160.0°; and ankle angles between 97.0° and 124.0°. Trunk angles for finalists 3 and 7 were relatively the same for the left and right foot contacts. In considering all finalists angles (Figures 4.31, 4.32, and 4.33), there were no significant outliers on either the left or right foot contact. Hip angles for all finalists were higher on the left foot contact than the right with a difference as low as 6.2° and 33.7° between the foot contacts. Finalists achieved knee angles above 130.0° with finalist 8 having the highest left knee angle (164.5°) and finalist

8 with the highest right knee angle (159.0°). Ankle angles above 100.0° were common among finalists, except for finalist 6 at 97.6° and finalist 5 at 99.1°, both on the right foot contact.

For toe-off during the maximal velocity sprinting, key joint angles were measured and reported for each finalist in Tables 4.34, 4.35, and 4.36. Based on finalists (3, 5, 6, and 7) who ran sub-11 s, trunk, hip, knee, and ankle angles were also closely noted.

	FINALIST 3		FINALIST 5		FINALIST 6		FINALIST 7	
Joint Angle	**Left (°)**	**Right (°)**	**Left (°)**	**Right (°)**	**Left (°)**	**Right (°)**	**Left (°)**	**Right (°)**
Trunk (α)	80.7	81.4	-	-	-	-	79.2	86.3
Hip (γ)	206.1	207.1	197.7	196.6	194.0	192.3	204.9	207.8
Knee (β)	150.7	153.3	146.4	139.8	142.1	146.8	157.9	150.3
Ankle (ι)	145.7	146.3	136.6	133.8	131.0	134.7	134.0	131.8

Table 5.3. Comparison of four angles between sub-11 second finalists on *toe-off* during maximal velocity phase. (*Note: Dash, '-', represents an angle value that was impossible to obtain due to technical limitation.*)

Among the sub-11 finalists, trunk angles were between 79.0° and 87.0°; hip angles between 190.0° and 208.0°; knee angles between 141.0° and 158.0°; and ankle angles between 130.0° and 147.0°. Interestingly for all finalists (Figures 4.34, 4.35, and 4.36), trunk angles on the left foot contact were lower than the right foot on toe-off. Hip angles between the left and right foot contacts were close in value with a difference of less than 2.0° for six finalists. Knee angles in the 140.0 – 150.0° range and ankle angles

130.0 – 140.0° or less for the left and right foot contact on touchdown appeared to be common among finalists. Finalist 9 was an outlier with knee angles of less than 143.0° on both foot contacts, an ankle angle of 135.4° on the left, and less than 130.0° on the right ankle.

Correlations between these four postural characteristics (the average of the left and right foot contacts for the trunk, hip, knee, ankle angles) and speed times (refer to 30 – 60-m (s) in Table 4.14) reached within the 30-m fly maximal velocity phase were calculated. The highest correlation ($r = 0.67$) was found between the ankle angle at touchdown and 30-m fly time. The next highest correlation ($r = 0.29$) was between trunk angle at toe-off and 30-m fly time. All other correlations were below 0.22 starting with the trunk angle at touchdown ($r = 0.13$); hip angle at touchdown ($r = -0.15$); hip angle at toe-off ($r = 0.14$); knee angle at touchdown ($r = 0.33$); knee angle at toe-off ($r = 0.20$); and ankle angle at toe-off ($r = -0.02$).

Correlations between the same four postural characteristics and final race time by finalists were highest in the ankle angle at touchdown and the hip angle at toe-off. A $r = 0.52$ and $r = 0.50$ correlation values were determined between these angles and final race time, respectively. Correlations within the 0.20 – 0.35 range included the trunk angle at touchdown ($r = -0.29$), hip angle at touchdown ($r = -0.26$), and knee angle at touchdown ($r = 0.31$). Smaller correlations were found between the trunk angle at toe-off ($r = -0.13$), knee angle at toe-off ($r = 0.03$), and ankle angle at toe-off ($r = 0.12$).

Among the strongest correlations values found between 30-m fly times and joint angles, and official race times and joint angles, hip extension at toe-off ($r = 0.50$) during maximal running was a factor in the sprint phase. Ankle joint angles appeared to play the largest role in maximal running velocity at touchdown (*r* = 0.67) and toe-off (*r* = 0.52). This suggests the quality of the foot strike and push-off during maximal sprinting is critical. It allows for a sprinter during maximal velocity to benefit from ‘front side’ mechanics during the late swing phase and aim effective ground contact to produce vertical force in an upright postural position (von Lieres und Wilkau et al., 2018).

Along with postural characteristic angles, the minimum knee and minimum ankle values, and the absolute change in joint angles, for left and right foot contacts, were reported in Tables 4.37 and 4.38. Outliers were seen in finalist 8 showed a 23.3° left knee angle change and 20.0° right knee angle change. All other finalists had knee angle changes of less than 15.0° on the left foot touchdown and less than a 22.0° knee angle change on the right foot touchdown. For minimum ankle angles, finalists were between 80.0-95.0°, except finalist 8 was at 79.0° on the right foot touchdown. Outliers in the change of ankle angle included finalist 6 (right foot, 9.7°). These changes in ankle angles were well below the mean values of 27.2° for the left foot and 22.2° for the right foot. It can be inferred that the minimum knee and ankle values reflect a sprinter's ability to execute the mechanics needed to prepare for ground contact and take-off. As a result, the sprinter is unable to recover during the sprint cycle and achieve maximal ‘front side’ mechanics while minimizing ‘back side’ mechanics (Mann, 2015). Known to coaches, recovery reflects the acceleration of the thigh to reduce the amount of time needed to recover the thigh through an optimal range of motion (Seagrave, 2009).

Therefore, coaches must assess the support and swing phases during maximal velocity to develop and correct sprint mechanics that require vertical ground reaction forces. Mann (2015) observed that force (created by ankle, knee, and hip moments) results occur in the first half, rather ‘front side’, of ground contact and is greater than forces occurring in the last half, ‘back side’ in maximal velocity sprinting. The sprinter who spends more time in ‘front side’ mechanics will have a better advantage and prevail over time (Mann, 2015). Overall, postural characteristic angles underpin implications for coaches must consider in preparing athletes from a mechanical and technical standpoint.

Asymmetry in Maximal Velocity

For the purposes of this project, perfectly symmetrical represent values closer to 0% whereas perfectly asymmetrical represent values closer to 100% (Bissas et al., 2022). Maximal velocity results revealed some variability between left and right foot contacts for select kinematic parameters suggesting functional asymmetries. Five parameters were assessed for asymmetry with the acceleration phase: CM horizontal velocity, DCM TD, DCM TO, foot horizontal velocity, and foot vertical velocity.

Table 4.26 shows CM horizontal velocities for left-right and right-left contacts. There were two finalists (finalists 3 and 4) that had more than a 0.35 m/s difference between foot contacts, with finalist 6 having the lowest difference of 0.01 m/s. Finalists 8 and 9 both had 0.08 m/s 5 other finalists were under 15.00 m/s difference. The asymmetrical percentage differences for all finalists were under 2.0%.

DCM TD and DCM TO parameters in Table 4.27 also reported left and right contact values that exhibited possible asymmetry. For DCM TD, finalists 5 and 7 were the highest outliers at 0.13 m and 0.11 m difference. All other finalists were at 0.60 m or less between foot contacts. For DCM TO, finalist 6 was the largest outlier with a difference of 0.12 m. Finalists 4 and 9 had a difference of 0.04 m while all other finalists were at 0.03 m or less. Asymmetrical differences were between 1.9% and 12.6% for DCM TD among finalists, while all finalists were under 6.0% for DCM TO. Outliers included: finalist 5 (DCM TD percentage of 12.6% and 1.0% for DCM TO), finalist 7 (DCM TD percentage of 9.0% and 1.4% for DCM TO), and finalist 3 (DCM TD percentage of 5.2% and 1.1% for DCM TO. Percentages suggest asymmetry may have been present but inconsistent during competition within these kinematic variables. This coincides with inconsistent findings between kinematic parameters and maximum velocity sprinting among world-class sprinters (Bissas et al., 2022).

Tables 4.29 and 4.30 showed foot horizontal and vertical velocity pre-touchdown (TD) and touchdown (TD). Recall, positive velocities of these parameters indicated the foot moving forward relative to the running surface and negative velocities indicated downward movement of the foot's CM. Results revealed a mean between left and right foot contact of 3.13 ± 0.59 for foot horizontal velocity pre-TD and 2.21 ± 0.47 for foot horizontal TD. For foot vertical velocity pre-TD and TD, the means were -3.06 ± 0.24 and -2.52 ± 0.24, respectively. For all finalists, asymmetry percentage differences exhibited less than 15.0% for foot horizontal velocity pre-TD and less than 20.0% for foot horizontal velocity TD. All finalists except one were under 6.0% for foot vertical velocity pre-TD, whereas foot vertical velocity TD was under 12.0% for all finalists except one. Among kinematic parameters selected for symmetrical assessment, these percentages suggest most finalists were able to reach maximal velocities with minimal asymmetry between left and right foot contact.

Zifchock and Davis (2008) collected kinematic and kinetic data on 52 runners to compare symmetrical values for consecutive and non-consecutive foot strikes and found a mean difference of 1.8% between foot strikes. Exell et al. (2012a) found significant asymmetry in 39.0% of kinematic variables through their investigation of intra-limb variability on eight trained athletes during maximal velocity sprint running. In another study by Exell et al. (2012b), 1) the importance of considering intra-limb variability was identified, 2) asymmetry varied between eight male sprint-trained athletes highlighting the advantages of single-participant design, and 3) kinematic variables tended to show significant asymmetry. Trivers et al. (2014) specifically found: 1) positive correlations between knee and ankle symmetry and 2) runners who specialize in longer races have less symmetry than sprinters with prominent differences in the ankles, thus showing symmetry to be positively associated with sprinting performance. The above studies suggest coaches should consider observing and assessing touchdown and toe-off positions of each foot to see if any indications of asymmetry exist on the same foot strike or between foot strikes as speed is sustained through the maximal velocity phase.

5.3 JUMP DISCIPLINE – LONG JUMP

In the Women's long jump, the determinants associated with the acceleration, velocity, and asymmetry within the first phase—the approach run—were identified and evaluated as likely decisive factors relating to jump performances achieved. (*Note: All contested jumps were deemed to have adequate conditions for competition; location, track surface, and wind readings were noted but not factors included in this analysis).*

Jump Analysis of First and Preliminary Rounds

Meet results from the flights of the First and Preliminary Rounds (1^{st}, 2^{nd}, and 3^{rd}) were reported in Table 4.40, 4.41, and 4.42. These results provide jump coaches with: 1) the level of performance needed to be among the top jump competitors within flights to advance, 2) how jump performances compared to season bests and personal bests, and 3) what trends of improvement or regressions in jump performance may have occurred during the championship rounds. The results also suggest refinements that may have or could have been made in the technical execution between the first and preliminary rounds contested.

The seeding of the four flights in the first round were grouped based on season best marks, shortest to longest. The first flight had the shortest official season best marks while flight four had the best 12 season best marks. In the West Region, 7 of the 12 jumpers who advanced came from the fourth flight. In the East Region, 9 of the 12 jumpers who advanced came from the fourth flight. The first round in the West Region had a mean official mark of 6.21 m, with a high of 6.95 m and a low of 6.12 m. The East

Region had a mean official mark of 6.23 m, with a high of 6.64 m and a low of 5.46 m. An effect size of 0.06 was found in the first round between the West and East Regions.

To advance to the preliminary rounds, the minimum official mark was 6.39 m (West Region) and 6.23 m (East Region). The field of 24 jumpers (12 from the West, 12 from the East) who advanced had a mean and standard deviation of 6.53 ± 0.19 m in the first round. As individual regions, the top 12 jumpers in the West had a mean and standard deviation of 6.61 ± 0.19 m while the top 12 jumpers in the East were 6.45 ± 0.19 m. The effect size between these two regions was moderate at 0.93.

Coaches should look to prepare their athletes to reach a season's best mark that would place them in the most competitive flight. Being seeded in a more competitive flight may change the dynamics of how a jumper approaches competition.

Although the advancement process for horizontal jumps is not the same as the sprint disciplines, there is value in achieving a season best mark that seeds a jumper in a later flight. The results show more than 55% of jumpers who advanced to the preliminary rounds came from later first round flights. Interestingly, no preliminary round qualifiers posted an official mark better than their season best during the preliminary rounds, showing a shorter mean jump distance of -0.35 m. With only 3 attempts given in the first round to be among the top 12 finalists from each region, executing the phases of the long jump is critical to gaining an official mark competitive enough to advance. Therefore, an understanding of the mechanics and application of jump fundamentals to execute the approach phase is paramount to success in the proceeding phases.

Jump Finalists

Sub-section 4.3.2 provides further detailed information on long jump finalists. Between two contested preliminary flights on separate runways, the top nine jumpers advanced to the final. These nine finalists set a mean and standard deviation in the first three rounds of 6.44 ± 0.09 m. The non-finalists only achieved a mean and standard deviation of 6.14 ± 0.18 m, a difference of 4.7% in distance. There was a large effect size of 1.50 between the top nine finalists and the non-finalists. Of the final official competition marks, the top nine finalists had official distances 4% lower than their season bests, 6.52 ± 0.14 m compared to 6.77 ± 0.19 m, respectively. A large effect size of 1.50 was also found between the official distance and season best marks.

A minimum of 6.09 m was needed to advance to the final three rounds. Table 4.43 displays a comparison of the final official mark, season best mark, and personal best mark. Five finalists were able to improve their jump in the final three (4^{th}, 5^{th}, and 6^{th}) rounds while four finalists were not able to improve from the preliminary (1^{st}, 2^{nd}, and 3^{rd}) rounds. A 2.1% mean improvement in official marks was shown by the five finalists from the preliminary to final rounds. Although improvements were made during the jump series, jumper 4 was the only finalist to equal their season's best mark during the competition.

Figure 4.21 and Table 4.44 show the official marks achieved by the nine finalists through all rounds. Most notably, finalists 3 and 4 were the only two competitors to have experienced an upward trend in performance in the rounds. Finalists 5, 6, and 8 were the only three competitors to have experienced a downward trend in performance marks in the rounds. This suggests investigating associated determinants related to the approach run may highlight technical deficiencies occurring at take-off and into the jump flight during competition. Omura et al. (2005) findings support determining the effectiveness of the approach run based on accelerative and horizontal velocity characteristics.

Approach Phase

Sub-section 4.3.2.1 reports more detailed kinematic data on the approach phase of the best individual jump for seven finalists who competed on the same runway. All finalists, except one, had a right take-off leg. With respect to step characteristics, the last four steps before take-off were evaluated. Table 4.45 shows the SL of the last four steps. Small effect sizes of 0.48 (between the fourth-last and third-last step), 0.50 (between the third-last and second-last step), and 0.88 (between the second-last and last step) were found in SL. The SL of the last step was above 2.00 m for 6 of 7 finalists; above 2.08 m for 6 of 7 finalists on the second-last step; above 2.11 m for 5 of 7 finalists on the third-last step; and above 2.08 m for all finalists on the fourth-last step. Most notably, finalist 7 had the longest SL in the third-, second-, and last step with an increase of 7%, 10%, and 21% in each step respectively.

In assessing the SR of the last four steps (Table 4.46), finalists reached a high of 6.90 Hz in the fourth-last step, 6.06 Hz in the third-last step, 6.90 Hz in the second-last step, and 6.06 Hz in the last step. Effect sizes were moderate at 0.62 (between the fourth-last and third-last step), large at 1.93 (between the third-last and second-last step), and 1.69 (between the second-last and last step). All finalists except one had a reduction in SR from the fourth-last to third-last step, an increase in SR from the third-last to second-last step, and a reduction in SR from the second-last step to the last step. This suggests an adequate amount of control and conservation of speed are needed between the last two steps going into take-off. The change in SR between steps suggests a change in rhythm in the approach run and perhaps a loss in velocity on certain steps in preparation for take-off. Popov (1983), Schmolinsky (1983), and Hay and Nohara (1990) have shown a drastic change in SR should not be made or emphasized in preparation for take-off. Based on SR and SL findings in this project, it can be inferred that an appropriate SL coupled with an adequate SR was met for some finalists during acceleration contributing to the velocity, accuracy, and preparedness needed at take-off (Hay & Koh, 1988).

Tables 4.47 and 4.48 show the step width (SW) values of finalists during their approach phase. The SW was the largest on the last step for all finalists except finalist one. An increase in SW was seen in consecutive steps by finalist 4 [0.14 m (fourth-last), 0.19 m (third-last), 0.30 m (second-last), 0.37 m (last)] and finalist 7 [0.10 m (fourth-last), 0.14 m (third-last), 0.19 m (second-last), 0.18 m (last)]. Among all finalists, small effect sizes of 0.46 (between the fourth-last and third-last step), 0.39 (between the third-last and second-last step), and 0.53 (between the second-last and last step) were found in SW.

The change in step width between steps was also calculated and shown in Table 4.48. The largest changes were seen in finalist 2 with changes of 0.11 m (fourth to third-last), -0.17 m (third to second-last), and 0.22 m (second to last); and finalist 6 with changes of -0.16 m (fourth to third-last), 0.14 m (third to second-last), and 0.06 m (second-last to last). It can be inferred these two finalists produced a non-stereotyped step pattern where a lack of consistency occurred. This supports the need to have an accelerative step pattern allowing a jumper to place focus on their speed and its effect on the technical aspects of the jump (Robison, 1974; Linthorne, 2008).

Change in Center of Mass

As done at the 2017 London WC, step time, as the sum of flight and contact time, was measured. Tables 4.50, 4.51, and 4.52 present the flight, contact, and step time of the best individual jump of the 7 finalists analyzed. For flight time, the mean range for all steps was between 0.080 to 0.127 s, with the second-last step as the outlier with a mean of 0.080 s. For contact time, the mean range for all steps was between 0.102 to 0.110 s. Therefore, the step time mean range for all steps was between 0.189 to 0.229 s, with the second-last step as the outlier with a mean of 0.189 s.

It can be inferred that the last step is also the take-off foot. The fourth-last and second-last step are the same foot, while the third-last and last step are the same foot. Consequently, similar mean and standard deviation values were found between the fourth-last and second-last step, and between the third-last and last step for the flight time. Effect sizes were calculated between steps. Based on mean and standard deviations, a large effect size of 1.50 was found between the fourth-last (0.110 ± 0.02 s) and second-last (0.080 ± 0.02 s), while a trivial effect size of 0.16 was found between the third-last (0.123 ± 0.02 s) and last step (0.127 ± 0.03 s) for flight time.

Comparatively, the effect sizes for contact time between the fourth-last and second-last step, and between the third-last and last step was also calculated. Based on mean and standard deviations, a moderate effect size of 0.51 was found between the fourth-last (0.106 ± 0.005 s) and second-last (0.110 ± 0.01 s), while a trivial effect size of

0.06 was found between the third-last (0.103 ± 0.01 s) and last step (0.102 ± 0.02 s) for contact time.

The summation of the flight and contact time representing the step time (Figures 4.22 (fourth-last), 4.23 (third-last), 4.24 (second-last), and 4.25(last)) revealed the third-last and last step as taking longer amounts of time than the fourth-last or second-last step. These results suggest finalists underwent a change in CM height based on transitioning from accelerative efforts into final steps before take-off. This is supported by Hay (1993) and Linthorne (2008) who indicated that a change in CM height and position of sprint support phases occurs during a transition period and eventual transfer of velocity from phase to phase.

Horizontal Velocity

To assess the velocities reached during the final steps prior to take-off, horizontal velocity was calculated and shown in Figures 4.26 and 4.27. Through the fourth-, third-, and second-last steps, finalists 1, 2, and 7 showed an upward trajectory in horizontal velocity. On the other hand, finalists 3, 4, 5, and 6 all had a decline in horizontal velocity during the fourth-, third-, and second-last steps. It can be inferred that an upward trajectory showed the ability of finalists to maintain normal sprint action despite some lowering of CM, whereas a decline in horizontal velocity indicated the finalists' inability to endure a CM height change without a compromise in sprint velocity.

In the last step, over 50% of the finalists had a faster horizontal velocity in comparison to the second-last step. The mean and standard deviation change in horizontal velocity was 0.02 ± 0.24 m/s between the fourth-last and third-last step; -0.08 ± 0.13 m/s between the third-last and second-last step; and 0.08 ± 0.34 m/s between the second-last and last step. These means and standard deviations suggest variance in approach speed in the final steps but more importantly differences that exist in the techniques employed in those final steps.

Studies have found a jumper's attempt to preserve horizontal velocity but also generate adequate vertical velocity in the steps going through the take-off correlates with the lowering of CM (Nixdorf & Brϋggeman, 1983; Brϋggeman & Sušanka, 1990; Brϋggemann, 1994). Specifically, Nixdorf and Brϋggeman (1983) and Hay and Nohara (1990) characterize the third-last and second-last step as where lowering occurs along with a reduction of speed to support the change in CM height.

Correlation between the official mark and CM horizontal velocity of the final steps found coefficients to be r = -0.62 (fourth-last), -0.26 (third-last), -0.07 (second-last), and -0.55 (last step). Among the correlations, the fourth-last and official mark suggest the development of acceleration and generating horizontal velocity during the approach run as two factors that influence performance outcomes. The last step and official mark correlation suggest a transfer of horizontal velocity coupled with appropriate CM lowering allows for a vertical range of motion desired at take-off. These notions agree with those of Hay (1986) and Linthorne (2008) mentioned in sub-sections 2.5.2.1 and 2.5.2.3, respectively.

Asymmetry in Jumps

For the purposes of this project, perfectly symmetrical represent values closer to 0% whereas perfectly asymmetrical represent values closer to 100% (Bissas et al., 2022).

Jump results revealed an extensive amount of information regarding the last four steps leading into the take-off. Step lengths (SL), step rates (SR), step width (SW), and CM horizontal velocities were the parameters selected for asymmetry assessment in the last four steps. The variability seen in the data suggested functional asymmetry may have been a factor in performance.

In SL changes between the fourth-last and third-last step: a) two finalists had over a 10% change while all other finalists had a 7% or less change; b) four finalists had a 10% or more change between the third-last and second-last step; and c) and five finalists had changes of 10% or more between second-last and last step. The step rate between the fourth-last and third-last step increased for only two finalists, decreased for three finalists, and remained the same for one finalist. From the third-last to the second-last step all but one finalist increased their rate. Finally, all but one finalist decreased their rate from the second-last to the last step. Consequently, step velocities were reported as a product of SL and SR. Three finalists had a reduction in velocity from fourth-last to third-last; all finalists had an increase in velocity from the third-last to second-last; and all finalists but one had a decrease in velocity from the second-last to last step. Corresponding SL asymmetry percentage differences included: fourth- to third-last step (less than 4.0% for all finalists except one outlier at 6.6%), third- to second-last step (ranging between 1.0 – 5.5% for all finalists except one outlier at 6.1%), and second- to last-step (ranging from 2.5 – 5.0% for all finalists except one outlier at 7.5%).

Table 4.46 shows the step rates achieved by jump finalists in the last four steps. Changes in SR going from one step to the next varied in percentage in the last four steps. The mean change in rate was a 6% decrease from the fourth-last to third-last step, a 23%

increase in rate from the third-last to second-last step, and a 14% decrease from the second-last to last-step. Corresponding to SR changes between steps, asymmetry percentage differences revealed the fourth- to third-last step to have 5 finalists below 4.0%; the third- to second-last step to have 4 finalists above 6.0%, and the second- to last-step to have a varied range as low as 2.1% and as high as 11.0% among finalists.

Concerning SW in Tables 4.47 and 4.48, changes between the last four steps were noted. Step width changes may have exhibited minimal variability in stride patterns of the last steps in preparation for take-off. Finalists 2 and 6 were the outliers with a change of more than 0.10 m from the fourth-last to the third-last step. Similarly, three finalists had a change of more than 0.10 m from the third-last to the second-last step. Lastly, three finalists were outliers at 0.14 m, 0.15 m, and 0.22 m from the second-last to last step. Jumpers showed a change of 3% ± 9% (fourth- to third-last), 4% ± 9% (third- to second-last), and 5% ± 12% (second- to last). Asymmetrical percentage differences were as high as 33.8% (fourth- to third-last), 34.2% (third- to second-last), and 37.4% (second- to last). It can be inferred that asymmetry may have influenced step width in the last four steps prior to take-off but may have been the early stages of acceleration in the approach run.

These step characteristic values reflect individualization among jumpers. This is supported by variability found in the main kinematic parameters (SR and SL) in average or high-level performers (Maćkała, 2007). Percentage changes in SL and SR suggest bilateral asymmetry may have influenced the interaction between SL and SR and the vertical impulse associated with take-off (Theodorou, et al., 2017). Step velocity changes showed a mean of -9% ± 17% (fourth- to third-last), 31% ± 27% (third- to second-last), and -20% ± 18% (second- to last). When SR, SL, and SV changes are combined, a mean of: 1) a 9% decrease in SV attributed to a 4% SL and 6% SR decrease from the fourth-last to third-last step; 2) a 31% increase in SV attributed to a 7% SL and 23% SR increase from the third-last to second-last step; and 3) a 20% decrease in SV attributed to a 7% SL and 14% SR decrease from the second-last to last step. This suggests that an increase or decrease in speed reflected greater increases or decreases with SR. Furthermore, jumpers look to maintain a balanced step velocity with the most accurate foot placement possible at the board (Theodorou, et al., 2017).

CM horizontal velocities were shown in Figures 4.26 and 4.27 of the last four steps. Based on velocities reached among finalists, all finalists were under 1.0% difference except one (at a value of 1.3%) from fourth- to third-last; were at or lower than 1% from third- to second-last; and were under 2% from second- to last-step taken.

These percentages revealed less consistency between jumpers. It can be inferred that the technique used in preparation for take-off may dictate the role asymmetry plays in each proceeding step. Coaches should consider specific step characteristics and their symmetrical functionality on each limb during the approach run of the long jump. This would allow coaches to address possible technical deficiencies in the acceleration and velocity phases during the approach run.

5.4 PROJECT LIMITATIONS

The main limitations of this project were:

Participants: Of the overall sprint (*n* = 96) and jump (*n* = 96) participants within all rounds and flights included in the NCAA Championships, extensive detail on sprint (*n* = 9) and jump (*n* = 7) finalist participants analyzed was a small group. The intention of the project was to include the two days of competition from the semifinal and final rounds of both disciplines. Due to the magnitude of the project, the digitization of semifinals for the 100-m was not included nor was the digitization of both jump flights included due to flights of long jump being done on two runways, in which only one runway was calibrated. In addition, the height, weight, and leg length of each participant was not available to use for this study.

Captured segments: Due to the limited number of cameras, 10 m sections or smaller segments of the 100-m were not captured. As done at the 1987 Rome WC (Brϋggeman & Sušanka, 1990), biomechanical information reports were not produced and given to athletes and coaches after qualifying heats/rounds prior to finals in preparation for the final day of competition.

Research team: Due to COVID restrictions, access to the facility was limited. The author worked with a very reduced support staff in the preparation and conduction of the project before, during, and after the live 2021 NCAA Championships.

Data collection: Whilst there was always a three-dimensional approach to recording, the camera locations and subsequently the number of cameras becoming available were dictated by the organizers and a range of other practical constraints. This may have created suboptimal recording positions for certain athletes and race stages.

Data analysis: Whilst the digitizing process adhered to established principles and the digitizing operator exhibited high levels of accuracy and reliability following a substantial training period, the outcome variables, even after filtering, are still expected to have been affected by the following inevitable sources of “noise-error” which are inherent to the manual video analysis:

- Picture resolution
- Post event synchronization of cameras
- Block body segment views
- Color “noise” in parts of images
- Natural variability of digiting operator
- Absence of body markers
- Fatigue related to manual digitizing

However, the study offers significant ecological validity, and the data collection and analysis techniques were the only option for a competition of this nature.

Velocity calculations: Three types of velocities have been used throughout the results section. These have been obtained through different calculation techniques and therefore should not be compared against each other as they are expected to display different values. For instance, the mean race/phase speed is purely a calculation based on time data, the step velocity is derived from step length and step time, whereas the CM horizontal velocity has been calculated through full-body digitizing. CM horizontal velocity is considered the most accurate, however, all three are presented so there is a range of ways to communicate performance data to coaches and athletes.

5.5 RECOMMENDATIONS FOR FUTURE RESEARCH

Based on methods used for this project, future biomechanical data collections for NCAA Championships may consider including:

- Use of more cameras designated for each discipline.
- Camera placement to include more increments within select phases of the 100-m and the long jump.
- Variation in camera placement for each discipline (*Note: This will depend on the stadium layout and access restrictions due to media*).
- Calibration to occur before and after each day of competition (*Note: NCAA schedule and stadium access will vary per location*).

Based on project findings, factors that should be investigated to better understand and inform on how to prepare and improve performance may include:

- Capture of larger phases within sprint and jump disciplines for analysis.
- Comparative study on the relationship between acceleration, maximal velocity, or asymmetry between college athletes in major championships (e.g., Indoor Conference, Outdoor Conference, Indoor NCAA, and Outdoor NCAA).
- Biomechanical evaluation of select parameters on the differences between semifinals and finals in sprint disciplines (e.g., 200-m, 400-m) in major championships.

- Biomechanical evaluation of select parameters on the differences between qualifying rounds and finals rounds in college horizontal jump disciplines (e.g., triple jump) in major championships.
- Gathering anthropometric data (e.g., height, weight, leg length) of athletes (difficult to obtain due to NCAA rules and regulations adhering to HIPAA violations).
- A cross-sectional study of multiple collegiate championships.
- Prospective study on the trends of the top nine collegiate finalists in sprint and/or jump disciplines; how techniques and performance trend with these athletes, if and when, they become elite athletes competing at the world championship level.

5.6 CONCLUSIONS

In conclusion, this project creates a database of biomechanical parameters of top-level U.S. collegiate athletes during competition while updating existing parameters captured on sub-elite athletes. The kinematic analysis revealed where the sub-elite (collegiate) athlete sector currently exists relating to sprint and jump techniques.

Time sprint analysis confirms the importance of coaches preparing athletes to be amongst the top qualifiers out of their region for seeding purposes. Learning how to perform through competition rounds constitutes the development and sustainability of velocities that contribute to the demands of each sprint phase. The kinematic parameters evaluated within the acceleration and maximal velocity phases demonstrated the individuality of sprinters and how the optimization of leading parameters, SL and SR, direct and influence all other sprint characteristics.

Similar to the time sprint analysis, the jump analysis also demonstrated the importance of coaches preparing athletes to achieve a season-best mark to place them in the highest possible flight for advancement. In only three attempts, jumpers must be conditioned to create velocities in the horizontal and vertical directions where a limited loss in speed and a high accuracy in positions are made. The kinematic parameters evaluated within the approach run signified the importance of developing a step pattern where adjustments do not hinder but allow jumpers to navigate transitions between jump phases.

As seen in the first WC biomechanical analysis report, this project stayed true to form in gathering information about the collegiate level and addressing the aims behind a study of this magnitude. It was observed in collegiate Athletics championship competition: a) what performance determinants played a role in constructing high-caliber performances and b) what kinematic mechanisms and techniques were used. The standard for future reporting has been set and will continue to evolve based on the sports' development and technological advances.

This project illustrates a marketplace available for future sports science and performance to develop into. The marketplace may include but is not limited to NCAA sponsorship, coaching tools, and published work. It is reasonable to suggest projects of this type may:

- First, by demonstrating to the NCAA the value in biomechanical projects, this project serves as a 'proof of concept' to model future projects. This collegiate database is meant to draw others to explore. For example, if this data was available, what tools could be developed (seminars, phone app, etc.) to leverage this information?
- Second, just like the WC projects have done, this project opens the doors to future projects to answer questions about how athletes/coaches/scientists could communicate or could apply this information in publications. For example, this dataset could be used in the future to guide coaches in tiering athletes appropriately based on models for training purposes or assist coaches in two or three-dimensional analyses based on available equipment.
- Third, the demonstrated generation of this data could compel the NCAA to invest in evidence-based performance practices on NCAA sponsored sports such as Athletics, for example, to create athlete profiles to chart progressions and specific trends and precipitate the publishing of literature to offer new insights and

knowledge on performance parameters where an impact on sports research, sports medicine, and training practices could be made.

However, many of these ideas for future projects are dependent on how the coaching field will respond to the availability of this evidence-based measures, and it is premature to assume that coaches will be open to participation in large-scale data collection and sharing. This is a conversation that needs to be explored between coaches and scientists to find the common ground for understanding, appreciation, and communication.

Overall, this evidence-based project provided information on the kinematic trends and progressions of high-caliber collegiate performances and how the mechanisms of sprint and jump disciplines are expressed at the college level in competition. Perhaps trends at the collegiate level do not show a sub-elite level, but a movement in the sport which those defined as professionally elite can learn from. Therefore, the combination of understanding collegiate performances and the application of the fundamental principles of biomechanics can only further promote the sport of Athletics.

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