A BIOMECHANICAL AND ELECTROMYOGRAPHIC ANALYSIS OF ELITE SHOT PUTTERS AT A DIVISION I UNIVERSITY

A Dissertation
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

Roman Waldera

In Partial Fulfillment of the Requirements
for the Degree of
DOCTOR OF PHILOSOPHY

Major Department:
Health, Nutrition, and Exercise Sciences

April 2022

Fargo, North Dakota

North Dakota State University
Graduate School

Title

A Biomechanical and Electromyographic Analysis of Elite Shot Putters at a Division I University

By

Roman Waldera

The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

DOCTOR OF PHILOSOPHY

SUPERVISORY COMMITTEE:

Dr. Bryan Christensen
Chair

Dr. Joel Hektner

Dr. Joe Deutsch

Justin St. Clair

Approved:

April 19, 2022
Date

Dr. Yeong Rhee
Department Chair

ABSTRACT

In effort to understand the most optimal technique for shot put throwing, researchers have investigated the individual factors of the throw that may contribute to elite level performances. Two techniques are commonly utilized by shot put throwers, known as the glide and rotational techniques. Within research studies, electromyography (EMG) and kinematic motion capture (MOCAP) analysis technologies are common data collection tools utilized by the authors. Within the dynamic shot put throwing movement, muscle activations and kinematic positions demonstrated by a thrower in motion will vary throughout the four phases of the throw, which are commonly referred to as: initiation, flight, landing, and completion phase In the current analysis of shot putters (n = 12, Males = 6, Females = 6), EMG analysis was conducted on seven muscles throughout the four phases of the throw: Rectus Femoris (RF), Biceps Femoris (BF), Gastrocnemius (GAS), Triceps (TRI), Latissimus Dorsi (LAT), External Oblique (EO), and Gluteus Medius (GM). The majority of MOCAP data variables within the current study were analyzed in the landing phase: Shoulder-Hip (S-H) Separation and Trunk Angle in the X, Y, and Z planes. Additionally, the maximum height which the thrower achieves during the flight phase, referred to as Peak Height of Center of Mass (PCOM), was analyzed using MOCAP. Significant relationships were found between thrown distance and activation of RF, EO, LAT, and GAS, with some differences existing between technique groups. For MOCAP data, significant relationships were found between thrown distance and angles of trunk inclination and trunk lateral flexion, with some differences existing between groups of technique and sex. The findings of this study are practical to track and field coaches in their understanding of the muscle activations in various phases of the throw as well as kinematic positions exhibited by athletes in the landing phase.

ACKNOWLEDGMENTS

I must acknowledge the people in my life who have helped me in pursuit of my doctoral degree. Firstly, my advisor Dr. Bryan Christensen. From day one of my PhD schooling, he has been there to support me, while encouraging and fostering my academic and professional growth along the way. I am very grateful for the relationship Dr. Christensen and I have established, and take comfort in knowing I can count on his loyalty through my future professional and personal pursuits.

I would like to acknowledge my research supervisor and committee member: Dr. Joe Deutsch. He has continually helped me to identify and take advantage of the opportunities that exist within academia. Because of Dr. Deutsch's mentorship, I have become confident in my abilities to meet expectations and make an impact within my future career. He has also taught me numerous life lessons that will benefit me as I navigate the inevitable ups and downs within my journey.

I would like to thank my committee members: Dr. Joel Hektner and Coach Justin St. Clair. I owe a great deal of my statistics and research design understanding to the mentorship I've received from Dr. Hektner. The value he has added to my research ability cannot be put into words. I am grateful for his continued support, and am inspired by his ability to promote student progress and success within the classroom.

Coach Justin St. Clair is someone I've looked up to for a long time. Since he started coaching in North Dakota, I believe the sport of track and field in this region has only served to benefit. He has been recognized as "coach of the year" at the NCAA Division 1 more than once, establishing him as one of the most knowledgeable, but he still has been eager to assist with this research investigation, and learn from the results to further improve his coaching. This demonstrates the true nature of his success: always finding a way to improve, no matter the level of success you've already achieved.

I must acknowledge my fellow-PhD student colleagues and friends: Kyle Collins, Lukus Klawitter, and Adam Bradley. They have been there for me on numerous occasions, offering unwavering help and encouragement. I am very thankful for the support they have all provided, and cherish the memories I have made with them through our PhD journeys. I know our group synergy will continue to grow throughout our careers as it has here at NDSU.

Finally, and most notably, I want to express the deepest appreciation and love for my family members. Especially my parents, grandparents, sister, and brother-in-law. They have continued to encourage me in pursuit of my goals, and have supported me in ways that I cannot repay. The greatest motivators in my life have always been the work-ethic and character exhibited by my family members, and I thank them for setting such a great example for me.

DEDICATION

I dedicate this disquisition to all of the track and field coaches who have mentored and inspired me throughout my career. The sport of track and field has always been a significant part of my life. The coaches I have had, worked alongside, and coached against have helped me to reach my highest potential within the sport. Through all of their actions, they are dedicated to helping track and field athletes optimize performance, and this disquisition is the best contribution I can make to support them in their pursuits, as they have aided me in mine.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

LIST OF ABBREVIATIONS

1RM ....1 Repetition Maximum

3-D 3-Dimensional

BF...Biceps Femoris

EMG..Electromyography

EO ....External Oblique

GAS...Gastrocnemius

GM ....Gluteus Medius

IAAF ....International Association of Athletics Federations

HRD ....Horizontal Release Distance

LAT...Latissimus Dorsi

m ....Meters

MOCAP ....Motion Capture

PCOM ....Peak Height of Center of Mass

PEC ....Pectoralis Major

PPO ....Peak Power Output

RF..Rectus Femoris

S-H ....Shoulder Hip

ST ....Semitendinosus

T&F...Track and Field

TRI ....Triceps

VL ....Vastus Lateralis

VM ....Vastus Medialis

CHAPTER 1. INTRODUCTION

Track and field (T&F) is a sport that is competed in by individuals throughout the world. While its emergence came from ancient accounts of the Olympics in Greece (776 B.C.), the first officially governed competitions began in 1866, with the first modern Olympics beginning in 1896 (Todd, 2020). T&F is still an Olympic event, as well as a popular amateur and professional sport discipline internationally. The International Association of Athletics Federations (IAAF) currently serves as the international governing body for the sport, and their rules for the 44 events (across the categories of running, walking, throwing, jumping, vaulting, and multi) tend to be congruent for athletes at the national and collegiate levels (Valmon, n.d.).

The T&F throwing events consist of the javelin, hammer, discus, and of particular interest in this paper, the shot put. Shot put athletes throw a weighted spherical implement to a maximal distance, after a short run-up confined to a seven-foot-diameter circle with a raised board following the front edge of the circle (Purves, 2018). To be successful, competitors must achieve high levels of strength, speed, and technical efficiency (Judge, 2012). That said, shot put athletes have been improving within those aspects since the time of the first modern Olympics, where the men's gold medal was won with a throw of 11.22 meters (m). The current men's outdoor world record is now 23.12m.

In order to surpass record distances previously mentioned, shot put athletes and coaches must fully understand the intricacies of the complex throwing movement. In effort to produce the most optimal technique, researchers have investigated the individual factors of the throw that may contribute to elite level performances (Ariel et al., 2004; Bartonietz, 1995; Byun et al., 2008). A variety of methods have been utilized in said research; the presence of several research-oriented strength and power training interventions for shot put athletes lend a substantial body of knowledge regarding annual periodization and implementation of training programs (Judge, 2007; Judge & Bellar, 2012; Oliveto, 2004; Stone et al., 2003; Waller et al., 2004; Zaras et al., 2013).

In addition to training studies, researchers have also performed biomechanical analyses of athletes performing shot put attempts. Within these research studies, electromyography (EMG) (Howard et al., 2017; Kyriazis et al., 2009; Terzis et al., 2007) and kinematic motion analysis (Byun et al., 2008; Coh & Stuhec, 2005; Harasin et al., 2010; Hubbard et al., 2001; Linthorne, 2001; Manesh et al., 2016; Saračević et al., 2018; Young, 2009) technologies are common data collection tools utilized by the authors. EMG is a voltmeter that records increases or decreases in voltage that occur within muscle fibers; these depolarizations precede and hence facilitate the contraction of a muscle (Vigotsky et al., 2018). A kinematic motion analysis, or motion-capture (MOCAP) analysis, consists of the measurement of velocities, positions, and accelerations of one or more body parts, often measured in three dimensions (Kaufman & KaiNan, 2017).

Purpose

While the findings of these researchers have been used to form conclusions regarding muscle activation and kinematic variables that may be associated with shot put success, an analysis utilizing both data collection methods within the same sample of elite throwers was not found in the literature A muti-dimensional investigation incorporating both of these methodologies into the same study is not uncommon in other paralleled sport disciplines such as sprinting (Yu et al., 2008), long jump (Mackala et al., 2013), pole vault (Bassement et al., 2008), and Olympic weightlifting (Chen et al., 2013). Therefore, this investigation includes a multi-dimensional biomechanics analysis of a sample of elite shot putters in Fargo, ND. Data collected from MOCAP and multi-muscle EMG analyses were used to compare muscle activations in reference to body segment position during shot put throws. In addition, data from these two methods were used to explore the relationships between the strength and power abilities of the shot put athletes and throwing distance.

Within previous MOCAP and EMG analyses of the shot put throw, researchers tended to analyze kinematic and muscle activation values in reference to the distinct phases of the shot put throw. Within the dynamic shot put throwing movement, muscle activations and kinematic positions demonstrated by a thrower in motion will vary throughout the four phases of the throw, which are commonly referred to as: initiation, flight, landing, and completion phase (Harasin et al., 2010; Howard et al., 2017; Hubbard et al., 2001; Kyriazis et al., 2009; Linthorne, 2001; Manesh et al., 2016; Saračević et al., 2018; Terzis et al., 2007; Young, 2009).

In the current study, EMG analysis was conducted on seven muscles throughout the four phases of the throw. Four of the muscles chosen for the current analysis have been included in previous EMG studies of shot put performance: Rectus Femoris (RF), Biceps Femoris (BF), Gastrocnemius (GAS) (Howard et al., 2017), and Triceps (TRI) (Terzis et al., 2007). Three of the muscles chosen were exploratory, with limited research available to necessitate their inclusion: Latissimus Dorsi (LAT), External Oblique (EO), and Gluteus Medius (GM).

MOCAP analysis researchers have found the most significant relationships between kinematic positions and thrown distance to exist within the landing phase (Bajric et al., 2017; Göksu & Kural, 2019; Harasin et al., 2010; Saračević et al., 2018, Young, 2009). Therefore, the majority of MOCAP data variables within the current study were analyzed in the landing phase. The landing phase variables were chosen given significant findings in previous research (Bajric et al., 2017, Manesh et al., 2016, Saračević et al., 2018, Young, 2009) and consisted of: Shoulder-Hip (S-H) Separation and Trunk Angle in the X, Y, and Z planes. Additionally, the maximum height which the thrower achieves during the flight phase, referred to as Peak Height of Center of Mass (PCOM), was analyzed in the current study given its previously identified associations with performance (Mileshin & Papanov, 1986; Young, 2004; Young, 2009).

The first purpose of this investigation was to identify which muscle activations and kinematic positions within the throwing movement, exhibited by the throwers in this sample, had the greatest effect on their throwing performance as measured by their throwing distance. Muscular activity and kinematic relationships were analyzed to determine relationships characteristic of all throwers in the sample, but also to identify any associations that are unique to any singular participant. Additionally, a second purpose of this study was to provide a comparative analysis of glide and rotational techniques to reveal how relationships between distance thrown, muscle activations, and kinematic positions differed for glide and rotational shot put throwers in the sample.

Hypotheses

It is logical to assume relationships exist between distance thrown and some kinematic and EMG values during shot put attempts as well as strength abilities and power abilities. Therefore, these variables were explored within an individual's shot put performances and amongst a sample of different shot put athletes. The first hypothesis was that the magnitude of EMG muscle activations (RF, BF, GAS, TRI, LAT, EO, and GM) during different timepoints of the throwing movement would relate to the measured distance of shot put throws. Likewise, a second hypothesis was that a thrower's body positions (Trunk angle in the X, Y, and Z planes in the landing phase and PCOM in the flight phase) during the throwing movement (measured with MOCAP) would relate to measured distance. The third hypothesis was that the relationships between measured throwing distance and MOCAP or EMG variables, would differ for throwers utilizing the two techniques: glide and rotational

Significance of the Study

This study is significant due to the number of muscles included within EMG, providing an understanding for muscle activity of seven muscles, from both the lower and upper body. Additionally, this study is significant because both EMG and MOCAP data collections were achieved simultaneously during throwing attempts. Few studies have provided EMG analysis of more than four muscles and were often limited to either the lower or upper body only. Likewise, a study of shot putters using EMG and MOCAP simultaneously is yet to be conducted. Finally, the sample of throwers in this study could be considered elite, as it consists of National Collegiate Athletic Association (NCAA) Division-1 (D1) and professional shot putters.

Limitations

Because this study is limited to athletes within a NCAA Division 1 ability level and within the midwestern portion of the United States, the ability to generalize findings may be limited. Additionally, the data collection takes place in a practice-setting, where a competition-like atmosphere will not be simulated, and therefore results may not be fully generalizable to the performance of shot put during competition. Further, the data-collection measurement devices could have impeded performance, as the participants' bodies were affixed with multiple motion-capture place markers and EMG units during throwing trials, which may have restricted natural movement of the body and extremities. The timing and schedule of data-collections may have served as a limitation. Some participants were scheduled to perform their trials earlier in the day than their usual training time. Also, some participants had to prolong their warm-up time while the research team was preparing the data collection devices. Lastly, the data collections took place in early January, and therefore the participants had just returned to campus from a three-week long semester break, and had not participated in organized shot put practice with a coach present in the weeks prior to data collection.

Assumptions

One assumption of this study is in regards to the participants' throwing techniques. It is assumed that the participants will utilize either the glide or rotational techniques, as described in this paper, and no other technique or derivatives of aforementioned techniques. It is also assumed that participants will attempt to throw the shot put to a maximal distance in their attempts, as instructed, refraining from utilizing submaximal efforts during the trials.

References

Ariel, G., Penny, A., Probe, J., Rudolf, B., Simonsen, E., Finch, A., & Judge, L. (2004). Biomechanical analysis of the shot-put event at the 2004 athens olympic games. *Ariel Dynamics*. http://www.arielnet.com/pages/show/adi-gba-01359/shotput-2004

Bajrić, O., Biberović, A., Saračević, Z., & Mikić, B. (2017). Influence of angular values of body segments on the distance of the throw out in (Z) axis. *Sports Science and Health, 7*(1),13-21. doi:10.7251/SSH1701013B

Bartonietz, K. & Borgstrom, A. (1995). The throwing events at the World Championships in Athletics 1995, Goteborg - Technique of the world's best athletes Part 1: Shot put and hammer throw. *New Studies in Athletics*, *10*(4), 43-63.

Byun, K. O., Fujii, H., Murakami, M., Endo, T., Takesako, H., Gomi, K., & Tauchi, K. (2008). A biomechanical analysis of the men's shot put at the 2007 World Championships in Athletics. *New Studies in Athletics*, *23*(2). 53-62. http://www.richwoodstrack.com/rhs_team_area/throws/shot/tech_Biomechanical%20Analysis%20Worlds%202007.pdf

Chen, S., Wu, M., Huang, C., Wu, J., Guo, L., & Wu, W. (2013). The analysis of upper limb movement and EMG activation during the snatch under various loading conditions. *Journal of Mechanics in Medicine and Biology, 13*. 10.1142/S0219519413500103.

Coh, M. & Stuhec, S. (2005). 3-D kinematic analysis of the rotational shot put technique. *New Studies in Athletics*, *20*(3), 57-66. http://www.richwoodstrack.com/rhs_team_area/throws/shot/tech_Kinematic%20Analysis%20Rotational.pdf

Göksu, Ö. & Kural, D. (2019). Evaluation of the effects of hip joint range of motion and trunk rotation on throwing biomechanics of shot putters: A pilot study. *Acta Medica Mediterranea*, *35*, 2823. 10.19193/0393-6384_2019_5_444.

Harasin, D., Milanović, D. &, Čoh, M. (2010). 3D kinematics of the swing arm in the second double-support phase of rotational shot put- elite vs. sub-elite athletes. *Kinesiology, 42*(2), 169-1774.

Howard, R. M., Conway, R., & Harrison, A. J. (2017). Muscle activation sequencing of leg muscles during linear glide shot putting. *Sports Biomechanics*, *16*(4), 463-484. doi:10.1080/14763141.2016.1246601

Hubbard, M., de Mestre, N. J., & Scott, J. (2001). Dependence of release variables in the shot put. *Journal of Biomechanics*, *34*, 449-456. https://pdfs.semanticscholar.org/9fe8/fc595ce6a286b338fba301feb2db04b50f01.pdf

Judge, L. W. (2007). Developing speed strength: In-season training program for the collegiate thrower. *Strength & Conditioning Journal*, *29*(5), 42-54. https://web.a.ebscohost.com/ehost/detail/detail?vid=17&sid=bd3b0515-023f-4905-9efc-073982f1e422%40sessionmgr4008&bdata=JnNpdGU9ZWhvc3QtbGl2ZSZzY29wZT1zaXRl#AN=27712920&db=sph

Judge, L. (2012). Spin to win: the rotational shot put. *2012 Iowa State High School Clinic*. https://www.championshipproductions.com/files/tc-02012/Judge-Rotational-Shot-Put-Spin-to-Win.pdf

Judge, L. W. & Bellar, D. (2012). Variables associated with the of personal best performance in the glide and spin shot put for U.S. collegiate throwers. *International Journal of Performance Analysis in Sport, 12*(1), 37-51, DOI:1080/24748668.2012.11868581

Kaufman, K. & KaiNan, A. (2017). Biomechanics. In Firestein, G. S., Budd, R. C., Gabriel, S. E., McInnes, I. B., O'Dell, J. R. (Eds.), *Kelley and Firestein's Textbook of Rheumatology (Tenth Edition)* (pp.78-89). Elsiever.

Kyriazis, T. A., Terzis, G., Boudolos, K., & Georgiadis, G. (2009). Muscular power, neuromuscular activation, and performance in shot put athletes at preseason and at competition period. *Journal of Strength and Conditioning Research*, *23*(6), 1773-1779. doi: 10.1519/JSC.0b013e3181b3f91e

Linthorne, N. P. (2001). Optimum release angle in the shot put. *Journal of Sports Sciences*, *19*(5), 359-372. DOI: 10.1080/02640410152006135

Mackala, K., Stodolka, J., Siemienski, A. & Coh, M. (2013). Biomechanical analysis of standing long jump from varying starting positions. *Journal of Strength & Conditioning Research, 27*, 2674-2684. https://doi.org/10.1519/JSC.0b013e31825fce65

Manesh, K., Murali, M., & Dhinu, M. R. (2016). Kinematic analysis of shot release of intercollegiate athletes. *International Journal of Physical Education, Sports and Health.*

3(5), 131-134. http://www.kheljournal.com/archives/2016/vol3issue5/PartC/3-4-73-958.pdf

Mileshin, L. & Papanov, V. (1986). Sergei Smirnov and Wolf Timmerman in the shot put. *Legkaya Atletika, 12*, 16-18.

Oliveto, N. (2004). Establishing volume load parameters: A different look in designing a strength training periodization for throwing events. *National Strength and Conditioning Association, 26*(5), 52-55.

Purves, L. (2018, November 16). *The history of shot put.* SportsRec. https://www.sportsrec.com/6582475/the-history-of-shot-put

Saračević, Z, Atiković, A., Štuhec, S. S., & Čuk, I. (2018). How kinematics influences shot put results in track and field of international level athletes (a case study). *Journal of Physical Education and Sport, 1*(73), 512-516. DOI:10.7752/jpes.2018.s173

Stone, M., Sanborn, K., O'Bryant, H.S., Hartman, M., Stone, M.E., Proulx, C., Ward, B., & Hruby, J. (2003). Maximum strength-power-performance relationships in collegiate throwers. *Journal of Strength and Conditioning Research, 17*(4), 739-45. https://www.semanticscholar.org/paper/Maximum-strength-power-performance-relationships-in-Stone-Sanborn/c52ead4650f83586c35e98e826f41732587bfd7d

Terzis, G., Karampatsos, G., & Georgiadis, G. (2007). Neuromuscular control and performance in shot-put athletes. *Journal of Sports Medicine and Physical Fitness, 47*(3), 284-90. https://ezproxy.lib.ndsu.nodak.edu/login?url=https://search.proquest.com/docview/202676574?accountid=6766

Todd, J. (2020, May 21). *The history of track and field.* FloTrack. https://www.flotrack.org/articles/6747663-the-history-of-track-and-field

Valmon, M. R. (n.d.) *Track and field events.* MomsTeam. https://www.momsteam.com/sports/track-and-field-events#

Vigotsky A. D., Halperin, I, Lehman, G. J., Trajano, G. S., & Vieira, T.M. (2018). Interpreting signal amplitudes in surface electromyography studies in sport and rehabilitation sciences. *Frontiers in Physiology, 8*. DOI:10.3389/fphys.2017.00985

Waller, M. A., Gersick, M. J., Townsend, R. J., & Ford, C. N. (2014). Strength and conditioning preparation for the transitional track and field thrower. *Strength and Conditioning Journal.,36*(6), 71-78. doi:10.1519/SSC.0000000000000102

Young, M. (2004). Critical factors for the shot put. *Track Coach, 166*, 5299-5304. http://www.coachkrall.com/Articles/Shot/shotcriticalfactors.pdf

Young, M. (2009). Development and application of an optimization model for elite level shot putting. *LSU Doctoral Dissertations, 25*. https://digitalcommons.lsu.edu/gradschool_dissertations/25

Yu, B., Queen, R. M., Abbey, A. N., Liu, Y., Moorman, C. T., & Garrett, W. E. (2008). Hamstring muscle kinematics and activation during overground sprinting, *Journal of Biomechanics, 41*(15), 3121-3126, https://doi.org/10.1016/j.jbiomech.2008.09.005.

Zaras, N., Spengos, K., Methenitis, S., Papadopoulos, C., Karampatsos, G., Georgiadis, G., Aggeliki, S., Panagiot, M., & Terzis, G. (2013). Effects of strength vs. ballistic-power training on throwing performance. *Journal of Sports Science & Medicine*, *12*(1), 130–137.

CHAPTER 2. LITERATURE REVIEW

Shot put is a track and field throwing event that has been revolutionized in style since its appearance in the first modern Olympics in 1896. The put of an Iron shot originated from boredom of the members of British gunboats over 100 years ago (Bartonietz, 1994). In the earliest shot put events, athletes used a side facing movement to initiate the throw. Eventually, shot putters utilized a throwing motion called the Glide, or O'Brien (named after its originator- American Shot putter, Parry O'Brien) style where the putter faces the back of the ring to initiate the movement (Judge, 2012). In the 1970's, shot putting with a rotational technique became popular; the main idea of this technique was borrowed from discus throwing. At that time, the world record was 58 feet. Since then, several competitors have thrown the shot put over 70 feet using the rotational technique (Lanka, 2000; Judge, 2012). Recently, the rotational style has become particularly popular among college and professional shot put athletes (Stepanek, 1989). The purpose of this literature review is to give a background of the glide and rotational shot put techniques and their technical parameters in order to determine components of successful throwers, as well as to establish gaps in the literature that will warrant future research.

The Glide and Rotational Technique Comparison

In order to understand the rotational shot put technique, the background of the biomechanical components of its antecedent, the glide, must be presented. Many kinesiological differences exist between the glide and rotational shot put techniques. The implications of advantages and disadvantages procured from each technique will be of importance in this review.

The Glide Technique

The decision to glide or rotate belongs to the individual; but, due to its consistent nature, most competitors begin using the glide technique (Manesh et al., 2016). More Olympic and world championships have been won by athletes utilizing the glide technique (Stepanek, 1989). The glide is more common among professional level women than men (Judge, 2012; Manesh, et al., 2016). Many factors contribute to the success of athletes using the glide technique. The glide technique can be separated into distinct technical phases for coaching and learning. 1 and Figure 1 outline the phases of the right-handed shot put throw as described by Stander (N.D.).

Table 1

Phases of the Glide Shot Put Technique (Stander, N. D.)

Name of Phase	Description
1. Initiation	With the shot put in hand, placed against neck. The trunk is lowered over the right leg as the athlete drives backwards off of the heel. The left leg lowers and kicks back into the air.
2. Flight	The once supporting right leg now performs a low hop to move across the ring and is then pulled back under the athlete's body in the center of the ring.
3. Landing	Both feet are now on the ground with the weight residing on the right leg. The right leg points away from the throw, the left leg points in the direction of the throw.
4. Completion	Still weighted, the right hip turns and extends in the direction of the throw, driving the rotation and extension of the shoulders and shot put at finish.

Some evidence suggests an advantage in the initiation of a gliding technique. The glide technique includes a short-long rhythm that improves conditions for leg inclusion during shot put delivery; whereas, the rotational technique shows the tendency of a long-short rhythm with harder conditions for leg work during delivery (Bartonietz, 1994). Contrary to the fluctuating velocities seen in rotational athletes, gliding promotes a more consistent increase in shot put velocity. Illustrated by researchers conducting video analysis of the men's 2007 world championship shot put competition, differences in shot put velocities occur in both techniques upon right foot touch down. When decreases in shot put velocities were compared, the decrease of velocity was much greater in the rotation than the glide (Byun et al., 2008). Overall, researchers have proven consistent application of velocity and rhythm using the glide technique has resulted in more Olympic and world champions than that of the rotational technique.

The Rotational Technique

More than four decades have passed since the first shot put throwers used the rotational technique, and its use remains prevalent today. All nine of the Men's Shot-Put finalists at the 2018 NCAA D1 Track & Field Championships were rotational throwers (NCAA, 2018). In a rotational shot put study, Coh and Stuhec (2005) outlined the phases of the movement for a right handed shot putter, which are shown in Table 2 and Figure 1.

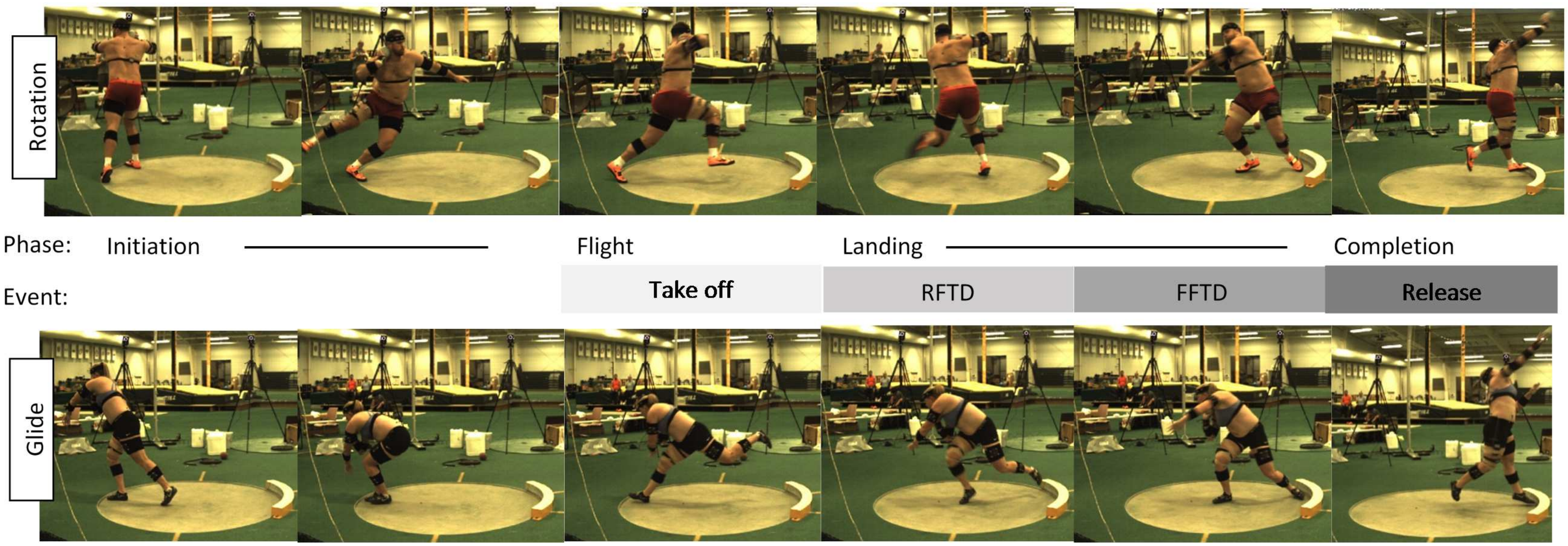
Table 2

Phases of the Rotational Shot Put Technique (Coh & Stuhec, 2005)

Name of Phase	Description
1. Initiation	Characterized by a phase of single support on the left foot as the right leg continues to swing wide around the back of the ring.
2. Flight	Transition of weight from the left to right foot at the middle of the ring. The end of this phase (right foot contact) marks the beginning of the next.
3. Landing	Starts when right foot is placed on the ground and ends when the left foot touches ground at the front of the ring
4. Completion	The final release action is performed.

Figure 1

Illustrations for the Phases of the Rotation and Glide Shot Put Technique



Note: RFTD- rear foot touchdown, FFTD- front foot touchdown

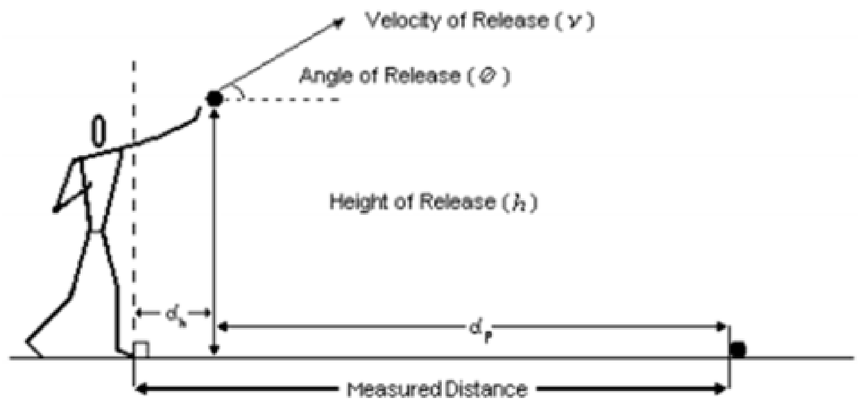
Coh and Stuhec (2005) reported the rotational technique as being an extremely complex movement requiring a high level of motor control and biomotor abilities of the thrower. Where glide shot put techniques have proved advantageous in consistency, velocity, and simplicity, the rotational technique also has its advantages. The rotational technique allows a longer period of force application on the shot, allowing the athlete to generate more horizontal velocity so that the shot is carried a longer distance (Judge, 2012). In summary, although very complex, the rotational shot put technique is relevant at elite level competitions and also has its advantages over the glide technique.

The Physics of Measured Distance

In shot put competition, an athlete's objective is to displace the shot put to the furthest measured distance. Researchers' have quantified the measured distance of a shot put using equations of physics. By regulation, the thrower must stay within the confines of a seven-foot diameter circle during the movement, and stay behind the front toe board throughout the release. Through a systematic analysis of scholarly shot put research and over 300 throwing trials, Young and Li (2005) states the total measured distance of a shot put is effected by two factors, the projected distance plus the point of measurement (Figure 2). The point of measurement corresponds to the distance of the athlete's foot relative to the toe board. Young also suggests the point of measurement at release is much less significant than the projected distance, as the distance between the foot and toe board varies so little in a movement confined to a seven-foot circle. To conclude, according to the measured distance equation, a shot put athlete should attempt to achieve their final double support phase as close to the toe board as possible to maximize distance; but, the success of the throw is far more affected by changes in the projected distance. Projected distance is calculated using the projectile motion equation (Figure 3), which is affected by the height, angle, and velocity of the shot put at the point of release. In addition to the research of Young, this equation is identified by authors conducting kinematic video studies of shot put trials (Coh & Stuhec, 2005; Hubbard et al., 2001; Linthorne, 2001). Individual shot put athletes exhibit differences in factors of height, angle, and velocity at release; these factors are referred to as release parameters. The projectile motion equation is a product of the measurements for an athlete's release parameters.

Figure 2

The Measured Distance of a Shot Put Throw (Young, 2009)



Note: The measured distance of the throw is equal to the sum of the horizontal release distance relative to the back of the toe board (dh) and the projected distance (dp) (Young, 2005).

Figure 3

The Projectile Motion Equation (Young & Li, 2005)

$$d_{projected} = \frac{v^2 \sin 2\theta}{2g}\left[1 + \left(\frac{2gh}{v^2 \sin^2\theta}\right)^{1/2}\right]$$

Where :
$d_{projected}$ - projected distance
v – release velocity
θ - release angle
g - gravitational acceleration, approximately 9.81 m/s²
h - release height

Note: The projected distance of a throw is a result of release velocity, release angle, and release height. Note that projected distance is a function of velocity squared (Young & Li, 2005).

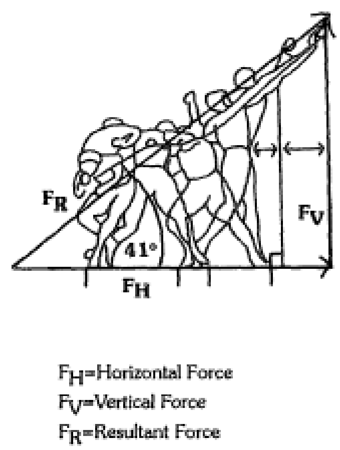
Release Parameters

Through examination of shot put parameters in regard to the projectile motion equation, increases in projected distance are a product of variances in release angle and velocity. The projected distance equation is least affected by release height. This is convenient because it is inherent and untrainable. Authors of kinematic video studies reported the height of release is primarily determined by an athlete's size and anthropometry (Coh & Stuhec, 2005; Hubbard et al., 2001; Linthorne, 2001; Young, 2005). There is little an athlete can do to change their genetically inherent anthropometric measurements. Therefore, due to increased height of release, it can be said that being tall and having longer limbs is advantageous. Since height of release is unique to each thrower, associations between angle or velocity of release and successful throws are more useful to coaches and researchers. The projectile motion equation includes velocity as a squared value, therefore it has the biggest impact on the distance of the throw. In a doctoral dissertation on critical shot put factors, Young (2009) introduces the practical implications of the projectile motion equation. Young (2009) explains, it is evident that release velocity has the greatest impact on performance as it has a quadratic relationship with the distance achieved, but it appears release velocity and angle are dependent on each other through an inverse relationship. With regards to the factors affecting projected distance, researchers and coaches tend to analyze release angle in attempt to optimize release velocity (Young, 2009; Harasin et al., 2010).

Measures of release height are unique to each shot putter through inherent genetic values, whereas release angle variations exist through varying technical traits of the thrower. Therefore, coaches and researchers have attempted to define optimal release angles to maximize the shot put's velocity at release, resulting in increased distance of the throw. In a non-peer-reviewed narrative, Pyka and Otrando (1991) use simple physics to indicate an ideal shot put release angle for all throwers. Where a summation of two vectors, horizontal force built up from the back of the ring and vertical force achieved from leg extension at the front of the ring, are applied to the shot put. The optimal angle of these summed vectors for a projected implement is 45 degrees (°), which provides for the furthest horizontal path. The authors indicate that the shot put however, is released from above the ground so the ideal angle is less than 45°. They defined the resultant angle of release as 41° (Figure 4).

Figure 4

Angle of Release as a Sum of Horizontal and Vertical Force Vectors (Pyka & Otrando, 1991)



This ideal angle (41°) is consistent with findings presented in a meta-analysis by Linthorne (2001). He used the methods of two shot put research studies to assess the validity for calculations of preferred release angle and optimum release angle. In this study, data from Mahera's (1995) unpublished dissertation study of five college shot putters and their release parameters are entered into Red and Zogaib's (1977) optimum release angle equation to compare the calculated optimum release angle and actual preferred release angle. Linthorne concluded, as the angle of release increases, the resistance the shot put places on the athlete also increases. An athlete with a steeper release angle requires more muscular force to overcome the shot put's increased resistance, which results in less force applied to the shot put (Linthorne, 2001).

Through his analysis, when the release velocity is held constant, there is an optimum release angle that maximizes the flight distance. This optimum release angle he determined is always less than 45°, but the optimum release angle approaches closer to 45° with increasing release speed. The results are consistent with the aforementioned 41° optimum angle presented by Pyka and Ontrando (1991) but indicate some variability. Overall, by using physics calculations without practical analysis of shot put throws, these two researchers agree on a release angle between 41 and 45°. A shot putter's release angle will affect the projected distance of the throw and should be acknowledged by coaches and researchers in its relationship with final release velocity.

Researchers have studied some of the best athletes and their measurements pertaining to the shot put release parameters. In a biomechanical analysis of the top three men's shot putters at the 2004 Athens Olympic Games using multiple high speed digital cameras (60 fps), release heights were greater than 2.3 m for all subjects (Figure 5) (Ariel et al., 2004).

Figure 5

Kinematic Performance Parameters of the top Three Shot Put Throwers at the 2004 Athens Olympic Games (Ariel et al., 2004).

Athlete	Result	Distance m	Release height m	Shot velocity m/s	Release angle Rad (deg)
Yuriy Belonog	Gold (1)	21.16	2.55	13.85	0.58 (33)
Adam Nelson	Silver (2)	21.16	2.33	13.95	0.58 (33)
Joachim Olsen	Bronze (3)	21.07	2.31	13.60	0.72 (41)

The researchers observed release angles of 33°, 33°, and 41°, respectively. Measured at 33°, release angles displayed by the top two competitors are much lower than Pyka and Ontrando's claim of 41° using the projectile motion equation. However, the third place competitor had a release angle of 41°. According to a narrative by Young 2004:

> USA Track and field high performance research has indicated that for humans the release parameters are optimized when the angle of release is between 31° and 36°. This is considerably lower than the mathematically 'optimal' range of 40° to 43° for elite throwers determined by using the projectile motion equation (p.6).

Therefore, Young stated that lower release angles are likely more optimal, which is validated by the results of Ariel et al.'s (2004) study.

For the three Olympians' shot put throws, researchers recorded release velocities of over 13.6 m/s and the measured distances were all greater than 21 m. In that event, first and second place shot putters Adam Nelson and Yuriy Belonog both recorded throws of 21.16 m with the same angle of release. It is important to note that Nelson achieved 7.2% higher release velocity than Belonog. Interestingly, Belonog was a taller athlete with a 9.4% higher release height, which made up for his slightly slower release velocity. For this reason, the researchers determined, given his movement parameters, Adam Nelson was closest to achieving optimal performance. Overall, Olympic shot put athletes with relatively similar values of measured distance exhibited differences in release parameters.

In a video motion analysis system study (ExpertVision, Santa Rosa, California) of two male collegiate shot putters using 200 Hz, the shot putter who was 0.8 m taller had release heights that were 0.16 m higher, as well as further shot put trials (Hubbard et al., 2001). This lends validation to the notion of an advantage for taller athletes. The shot putters in this study completed 36 trials, and were instructed to throw their trials with either low, normal, or high release angles. Mean release angles of 41.8° and 36° were measured for the best and second best throwers, respectively. The authors also found release speed decreases with increasing release angle at about 1.7 meters per second per radian ((m/s)/rad), quantifying the release angle and velocity relationship. The researchers determined athletes have greater potential for release velocity at lower release angles. Young (2009) wrote, “Although physics allows us to calculate optimal values for release, given the inverse relationship of release height and velocity, for any given thrower, as one of the parameters increases, the other decreases” (p. 4). This being said, the simplest ways to increase the release velocity, and thus measured distance, is to manipulate the release angle so that it maximizes release velocity while still maintaining an angle that will permit elite level distances. He concludes that this relationship is not practical for coaches and athletes to aim for exact angles, but rather to understand that lower release angles are optimal when they still permit elite level throws due to the increased horizontal displacement of the shot put in the direction of measurement. Overall, variations exist between the optimal release angles determined by interpretive research narratives of the projectile motion equation and those observed in the trials of shot put study participants.

The shot put velocity achieved during the final double support phase is the primary indicator of shot put distance. Authors of a video study using trials of a national-level Finnish male rotational shot putter used an Ariel Performance Analysis System (APAS) to measure release velocities of the final double support phase (Harasin et al., 2010). The researchers recorded velocities of 12.3-13.3 m/s during the athlete’s final phase of shot put delivery. The shot putter in this study was throwing at an elite level, with throws ranging between 19-21 m. Recall that the 2004 Olympic shot put athletes all surpassed the 21 m barrier with release velocities above 13.5 m/s. Release velocities recorded for the two collegiate throwers of Hubbard’s (2004) study were 11.22 and 11.52 m/s; the measured distances of the trials were not included, but were assumedly less than those of Olympic and national level athletes. In Coh and Stuhec’s (2005) video study of a male Slovenian national shot putter whose lifetime best was

20.56 m, they also used Ariel Performance Analysis System (APAS) software to record release parameters. Researchers measured a final release velocity of 12.94 m/s for the athlete's best trial of 19.58 m. Therefore, it appears final release velocities of national level shot putters are in excess of 12.5 m/s. The results of these studies indicate final release velocities can vary between two athletes who throw the same distance; and, velocities seen in throws of elite level athletes are greater than those of an amateur level.

The velocities required to throw the shot put to elite distances have been recorded, but the practical implications for achieving these final velocities are much more complex. Release velocity is the most important aspect for measured distance of a shot put and is affected by release height and angle given the projectile motion equation. However, the previously quantified release parameters detailed through research of the best shot putters, should not be used as a goal for shot put training. The projectile motion equation assumes all release parameters are independent of each other, like in a cannon or catapult. This is not characteristic of a shot putter's body. The author of a previously mentioned study suggests, "the human musculoskeletal system is an extremely complex system of levers and pulleys which do not function with equal capacities at all angles or positions, for this reason we should establish 'real world' critical factors for release parameters" (Young, 2005, p. 5). The biomechanical instances that lead to further shot put throws involve more than changes to the athlete's release parameters and will be outlined in the remainder of this literature review.

Kinematic Analysis

In previous sections of this literature review, results of 3-dimensional (3-D) motion analysis were described to establish the release parameters of Olympic and collegiate male shot putters. Researchers are beginning to look for more practical ways to achieve elite level release parameters. To optimize release parameters, the athlete must achieve specific positions and timing of the body and limbs at each phase of the movement leading up to release. Using 3-D video motion analysis, researchers measure the execution of these phases and refer to them as critical parameters. Therefore, optimal release parameters in shot put are often a product of an athlete optimizing the critical parameters of the movement.

Many critical parameters that researchers identify are congruent for both glide and rotational shot put techniques. However, the movements are not identical and therefor have been analyzed separately within kinematic research studies. Recall that as a squared value within the projectile motion equation, velocity of release is more impactful to shot put performance than angle and height of release (Young, 2005). Therefore, all movements of the athlete prior to release should be made in effort to optimize the velocity of the shot during the final phase of the throw. However, it has been determined that the acceleration of a rotational shot put throw is resultant of crossover acceleration throughout the four phases (Stefanović, 2017). Recall, glide technique athletes utilize a consistent increase in velocity throughout the movement.

Horizontal Release Distance (HRD)

To identify parameters that increase performance, the authors of a glide shot put study used two digital cameras and video motion software to observe 3-D coordinates of 22 body landmarks and the center of the shot for each throwing attempt (Manesh et al., 2016). The subjects were two male intercollegiate shot putters whose best trials were 10.86m (Athlete 1) and 10.67m (Athlete 2). Similar to aforementioned video studies, the release parameters (height, angle, and velocity of release) were recorded. However, the authors of this study also analyze the critical parameters leading up to release. They chose Horizontal Release Distance (HRD) as one parameter, referring to the horizontal distance between the center of the shot put and the inside-most surface of the toe board at the moment of release. Increased HRD is a benefit for an athlete under the right circumstances because the implement will be released at a point further from the toe board in the direction of measurement. In this study, HRD values and measurements of throws increase together. In the worst trial of the study, Athlete 2 showed a negative value for HRD (-.07m), meaning he released the shot put from behind the toe board. In the furthest trial of the study, Athlete 1 achieved an HRD of .09m. In Young and Li's (2005) study of seven of the top eight women who competed at the 2002 USA Track and Field National Championships, they also define and analyze HRD in the same way. This study is notable because few researchers have included elite women as subjects for shot put analysis. The authors chose 30 critical parameters to study with 3-D video analysis. Greater HRD values along with four other parameters recorded from the females using both rotational and glide were determined to increase performance (Figure 6). The top three women at the competition achieved an average HRD of 0.28 ± 0.09m and throwing distances of 18.43 ± 0.81m. Given the conclusions of these video studies that include male, female, elite, intermediate, rotational, and glide subjects; it is in good practice for coaches to cue athletes to increase HRD of the shot put.

Figure 6

Significant Parameters for Rotational Shot Put (Young & Li, 2005, p. 138)

Parameter	*Parameter estimate*	*F value*	*p*
Intercept	69.07	699	0.024
Rear knee angle at RFTD	−0.267	804	0.022
Release speed	−0.925	68.8	0.076
Rear knee angle at release	−0.097	2457	0.013
Shoulder-hip separation at release	−0.899	2233	0.014
Horizontal release distance	−0.255	122	0.058

RFTD – Rear foot touchdown

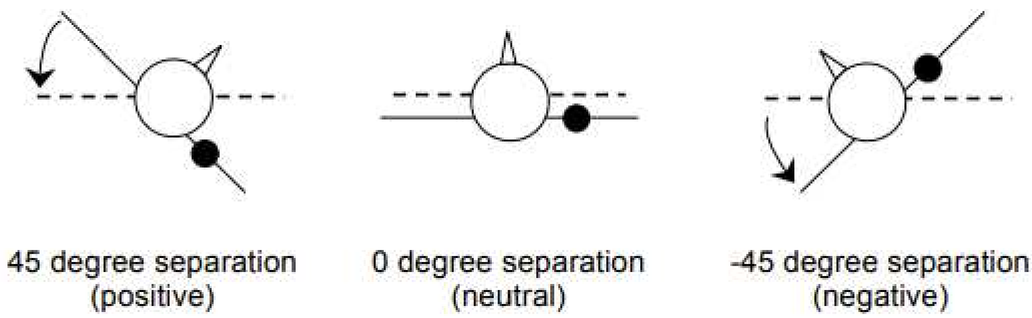
Note: Determined through results of a stepwise regression analysis (Young & Li, 2005, p. 138).

Release Position

Another critical parameter included in both research studies is the separation between shoulder and hip at release. It was one of the significant parameters ($p < 0.10$) of the women in Young and Li's (2005) study ($r = 0.72$, $p < 0.06$) as well as the two men in Manesh et al.'s (2016) glide study. This element of separation is measured in degrees, for the hips position relative to the shoulders (Figure 7).

Figure 7

Shoulder-Hip Separation for a Right-Handed Thrower (Young, 2009).



Note: The dotted line represents the orientation of the hips and the solid line represents the orientation of the shoulders. The small black circle represents the shot. The angle between the line of the shoulder and the line of the hip represents the shoulder-hip separation. For left handed throwers, these angles are reversed.

Young and Li (2005) found a correlation between performance and separation, which means athletes should strive for a more positive shoulder-hip angle prior to release. For this reason, shoulder-hip separation is a critical parameter for shot put performance in both the glide and the rotational techniques. This separation is suggested to create more momentum for the implement by promoting a blocking action of the non-throwing side (Bartonietz & Borgstrom, 1995). However, Young and Li (2005) concluded that separation is to be achieved at release and is not imperative at other phases of the movement. Overall, shoulder-hip separation is a parameter that has been proven to have an effect on the outcome of shot put attempts.

Statements from Young and Li (2005) explaining the importance of separation at release in comparison to the other phases of the throw can be further explained by the research of others. Bajrić et al. (2017) conducted a kinematic study of an elite-level international male shot putter (personal best: 20.73m). They analyzed video-recorded (three Sony cameras) movements with 3-D APAS software (Ariel Dynamics Inc., San Diego, CA) and defined the x-axis (length), y-axis (height), and z-axis (depth) for analysis. In regards to the final phase, he performed better when exhibiting smaller (z-axis) angular values at the L5 lumbar vertebra and S1 sacral region (Beta = -2.16, $p < .01$) and larger values of left shoulder angle to the level of the 7th cervical vertebrae (Beta = .77, $p < .05$) (Bajrić et al., 2017). Under this dictum, rotational throwers should attempt to achieve slightly more forward deviation of the spine and limiting backward fluctuation within the final phase of the throw. Also, the left arm should be elevated within the z-axis prior to release, which likely created an optimal projection angle for this thrower to maximize the release variables within the projectile motion equation resulting in the greatest velocity production at release.

In the final phase of the glide technique, throwers might achieve more optimal angles of release when the right hip allows more internal rotation and the left hip allows less external rotation (Göksu & Kural, 2019). This concept was introduced by researchers of a study in which goniometric measurements of adult glide technique shot putters (n = 9 males, 9 females) were compared to video (analyzed with Skill Spector V 1.3.2 and Dartfish Team Pro 5.5 programs) of their shot put trials (average distance: males = 11.92 ± 2.5m, females = 12.06 ± 2.12m). Given the throwers were right handed, this better promotes the concept of a rotating the dominant hip to improve shot put performance. In the same experiment, Göksu and colleagues also determined that female shot putters' demonstrating greater goniometric measured values of rightward lateral flexion of the trunk ($p < .05$) also achieved greater release velocity ($r = .82$) and thrown distance ($r = .72$) in throwing trials. This finding can be interpreted as a coaching cue: trunk lateral flexion and rotation in the power position should be achieved in the direction of the throwing side. Any rotations or flexions counter to the throwing side may impede performance within a glide technique throw. Also given the finding of internal rotation of the right hip, drills and throwing should include technical focus on the right hip turning into a braced left leg throughout the final phase of delivery.

Saračević et al. (2018) designed a case study in which one elite male shot putter (personal best: 21.07m) was studied using 3-D motion analysis via a Xsens MVN inertial suit system. In the experiment, 36 shot put trials were recorded in one day over two sessions. Kinematic analysis was limited to the time of final 0.1 seconds before release through release. Upon analysis of the recorded throwing attempts Saračević and colleagues only reported statistical significance in two relationships: the positive correlation between left ankle angle change to the x axis and performance; also, the negative correlation between angular velocity of upper left leg and t12 vertebrae and performance. The upper left leg and t12 vertebrae can be understood as the shot put thrower's non-dominant side. Thus, when considering the put of the shot, the non-throwing side of the body must decelerate and act as a solid block for the throwing side to rotate and extend around. The authors described this as a changing of the relative y axis to the non-throwing side of the body to create more tangential velocity of the hand and shot while the throwing side gains inertia. The authors also called this an open-ended kinetic chain, creating optimal conditions for the throwing arm. To explain the significant benefit of ankle change to the x-axis, the authors described how the left ankle further solidifies the non-dominant blocking position from the ground in this fashion. They conclude that coaches can use this information to improve performance through better strength and conditioning of the non-throwing side of the body.

Center of Mass During the Flight Phase

Recall that Young and Li (2005) studied the female finalists at the 2002 USA National Championships. In a near identical experiment, Young (2009) analyzed the techniques of female shot putters in the 2003 USA National Championship. He found “peak center of mass vertical displacement of the athlete-plus-shot system during the flight phase (PCOM)” (p.55) to be a factor significant to performance. Although previous research lends no measurements for comparison, Young reported mean values of 0.18 ± 0.05m. The significant relationship was in favor of increased PCOM. He expresses the flight phase’s benefit; the eccentric loading of lower extremities is achieved by shot putters as they land on their rear and front feet from the flight phase. This causes a stretch shortening cycle of the knee extensors, increasing their force producing capacity to aid in a powerful delivery of the shot put.

Leg Flexion

Of the five critical factors from Young and colleagues’ (2005) experiment that were significant in promoting shot put success, two of them were a measure of the athlete’s rear (dominant) leg. The authors state more flexion of the rear knee at both rear foot touch-down and release were highly attributed to increased measured distance. The necessity of increased flexion at rear foot touch-down agrees with current coaching principle. However, greater flexion of the rear leg at release contradicts the common shot put coaching inclination that complete extension of one or both legs is optimal for maximizing measured distance. The benefit in rear leg flexion was undefined prior to the results of this study. Young and Li (2005) suggest that:

> The initial force generated by the proximal-to-distal sequencing of hip extension, knee extension, and plantar flexion would accelerate the athlete and shot system with such rapidity that either the shot would be released before the complete extension of the more distal joints or the athlete would break contact with the ground, making further extension irrelevant. (p. 142)

They follow this statement by suggesting that further extension of the rear leg may not be beneficial, rather that it is unnecessary when the athlete is able to produce adequate implement acceleration while maintaining flexion of the knee. However, in his next experiment Young (2009) found that rear leg flexion at release is not significant to performance, and mean knee flexion angles became more extended from rear foot landing (116 ± 11 degrees) to front foot landing (122 ± 12 degrees) to release (147 ± 8 degrees), which were reported as similar to those of Young's first experiment. This finding resolved the disparity, agreeing more with previous coaching literature that supports extension of the legs throughout release. To conclude, greater flexion of the rear leg at both rear foot touch-down and release greatly influences measured distance in glide and rotational shot putting. It is likely due to the shifting of knee extensors into an advantageous position for force production upon flexion.

Kinematic Learning

In a final experiment, Young (2009) used the information gathered on the female shot put athletes in the first two experiments to provide an informative lecture/packet/DVD for a group of the female shot putters and their coaches. He also had a control group, comprised of elite USA female shot putters who receive no kinematic information regarding their throw. Using similar video analysis, he observed the change between athletes' original videos and video of throws from a different national championship meet, seeing whether the intervention group altered their technique more than the control group. He also ran statistics to see if the technique in these groups differed significantly in relation to the variables previously described (hip and shoulder separation, PCOM, and knee flexion at different stages of the throw). Finally, he performed t-tests to indicate whether or not there was a difference in groups for throwing performance. The results supported the hypothesis that the intervention group would experience performance improvements, $F(9, 12) = 3.91$, $p < .02$, however, it could not be concluded that it was attributed to the improvement on the eight variables. Of those eight variables, increased hip and shoulder separation at double support, $t(6) = 3.49$, $p < .01$, and rear knee flexion, $t(6) = -2.95$, $p < .03$, were significantly higher in the treatment group. Regarding the results of his experiments, Young explains that certain kinematic instances can be identified and achieved to improve performance of female shot put technique at an elite level. Overall, the context of improvements as a result of kinematic knowledge may not be fully understood. However, it appears that providing a technical model made individually for a shot put athlete from their kinematic motion data can serve to improve performance.

Power

In order to displace the shot put (men: 16 lb., women: 8.8 lb.) to a maximal distance, shot putters rely on their ability to produce muscular power (Zatsiorsky et al., 1981). According to Burnett (N.D.), power strictly is the product of force and velocity. In this capacity, training regimens that promote power production of shot putters may be of significant value. To achieve this, power training is utilized by throwers, which is often a combination of high intensity (75-90% 1RM) and speed-oriented (≤30% 1RM) weight training (Sakamoto et al., 2018). Power is the expression of strength at velocity. Since power output is maximum power production of an athlete during a brief moment, with a given set of circumstances, it is likely the most important aspect in improving the performance of shot putters (Stone et al., 2003; Zatsiorsky et al., 1981). The shot put throw requires an athlete to move a weighted object maximally in a brief period of time; thus, muscular power is a critical component of success for shot putters.

Tests of Power

Within training, power field tests (over-head-back shot put throw, standing shot put throw, 40m dash, and standing long jump) are common methods for coaches to assess their athletes' power production abilities (Zaras et al., 2019). While these power field tests are utilized at many levels of shot put training, the exact mechanism to which the tests predict performance may not be fully understood by the coaches and athletes. To test this notion, Zaras and colleagues (2019) designed an experiment where aforementioned field power tests were performed by throwers of different disciplines and compared to their throwing performance before and after a 10-week training intervention typical of track and field throwing athletes. They also monitored changes in Vastus Lateralis (VL) thickness. Zaras and his associates found for all throwing disciplines, the factor that most significantly influenced improvement in throwing distances was a regression model including over-head back shot put throw and VL thickness (6.5 MHz, MicroMaxx Ultrasound System, Sonosite, Bothel, USA) improvement from pre- to post-training period ($R^2 = 0.558$, $p = .016$, Backward Beta = 0.644, $p = .018$, Thickness Beta = 0.681, $p = .014$). This result is of value for coaches and athletes, suggesting common field tests may be valid for predicting performance but only when combined with alterations in muscle architecture. This notion was further supported in a similar study by Zaras et al. (2016), where six males and six females participating in various throwing events served as the participants. The model including pre- to post- training percent increases of VL length and thickness explained 33% of increases in track and field throws (adjusted $R^2 = 0.338$, $p = .06$, Length Beta = 0.703, $p = .028$, Thickness Beta = 0.511, *p* = .09.) (Zaras et al., 2016). Understandably, increased muscular thickness is likely characteristic of increased strength and more muscle mass. Both authors suggest that longer fascicle length may be advantageous in producing force later in the force time curve (100-250ms) which is indicative of the shot put final position throughout release. Athletes and coaches can best utilize these findings by monitoring training and field tests in regard to architectural changes of leg muscle fascicles.

Although the power field test results of the throwers in the Zaras et al. (2016) and Zaras et al. (2019) studies did not serve as standalone predictors of throwing performance for the given throwing disciplines, a relationship to tests of standing shot put throws was described. The standing shot put throw field test can be understood as the final release of the shot without preliminary glide or rotational movement. Therefore, it can be assumed to translate somewhat to rotational or glide shot put performance, and of significant interest to this study. Zaras et al. (2016) reported VL thickness increases from training explained 37% of the variation in the power position shot put tests ($p = .048$), while Zaras et al. (2019) found only a borderline significant relationship for those two variables ($r = -0.59$, $p = .056$). However, post-training correlations were significant between shot put power position improvements and standing long jump improvement ($r = 0.81$, $p = .003$) and 40m sprint improvements ($r = -0.63$, $p = .038$) (Zaras et al., 2019). Regression models including post-training improvements in calculated work production of long jump and increases in VL muscle thickness explained almost 80% of the increases in shot put standing throws (adjusted $R^2 = 0.799$, $p = .001$, work production long jump Beta = 0.726, $p = .001$, Thickness Beta = -0.400, $p = .026$) (Zaras et al., 2019). To conclude the findings of both studies by Zara and colleagues, the 10-week training interventions presented had a positive effect on the throwing events and standing shot put test performance. Looking at the increases in those measures, changes in VL muscular architecture can be a substantial indicator of progress towards increased throwing distances. Also, relationships between increased standing shot put throw, 40m dash improvements, and standing long jump improvements exist. When put in a model together with VL fascicle thickness increase, over-head-back shot put throw improvement or standing long jump improvement can significantly explain throwing distance increases, while the model including VL fascicle length increase tended to explain improvements in the standing shot put throw test. These results indicate that power field tests are valid for assessing throwing event training protocols, which had a positive effect on throwing performance. When regarded alone, no single test result explained increases in actual throwing event distance; but improvements in standing long jump and 40m dash are directly correlated with standing shot put throw improvements. Therefore, it is important to regard improvements in power field tests with changes in muscle architecture or within the context of other improvements such as standing shot put throw or over-head-back shot put throw. Overall, shot put athletes have opportunity to improve performance with the use of 10-week training interventions and power field tests described in both of the Zaras and colleagues' studies.

Much of the power in explosive events, like shot putting, comes from an athlete's legs. According to the aforementioned video study research presented by Coh and Stuhec (2005), the initial movement in the rotational shot put technique is generated by the muscles of the lower body and finalized by movement of the upper body at release, but the primary power is generated as a result of the action of the lower extremities. In a study of nine Greek national level rotational shot putters, Kyriazis et al. (2009) determined rotational shot put performance is better correlated with muscular power of the lower extremities than with absolute muscular strength. All of the subjects were male, with personal best throws between 14.19 and 19.98 m. The researchers came to their conclusion by testing vertical jump force, 1 repetition max (1RM) strength in the squat exercise, and the distance of shot put trials. They determined vertical jump values had a higher correlation to shot put performances ($r = 0.70$, $p < 0.05$) compared to 1RM squat, which had low and insignificant association. Vertical jump is a measure of muscular power; thus, the rotational style relies heavily on the athlete's ability to produce muscular power with their legs.

Power-Strength Relationship

The 1RM squat signifies a measure of absolute muscular strength. Although less correlated with performance, a certain base level of absolute strength is required for shot putters of either technique to then develop the required level of muscular power. For example, Judge and Bellar (2012) reported 1RM strength values of bench press ($r = .767$), back squat ($r = .771$), and power clean ($r = .868$) measured at pre-season to be correlated ($p < .001$) to shot put personal best performance during the competitive season for elite collegiate shot putters ($n = 24$ males, 29 females; personal best = 16.93 ± 2.45m and 15.24 ± 2.84m, respectively). They also reported glide shot put athletes to have significantly higher ratios of bench press strength to personal best throw for both males ($t = 2.132$, $p = 0.044$) and females ($t = 3.166$, $p = 0.004$). The aforementioned research outcomes present an interesting relationship between strength and power for elite rotational shot putters. This concept was described well by Judge and Bellar (2012) in their study of shot put athletes:

> Power is the product of force and velocity and as a result, changes in force produce changes in power output. But, it should be noted that increases in force are generally offset via decreases in velocity such that maximum power is generally achieved while utilizing around 30% of an individual's maximum strength (p.39).

The evidence presented by these researchers suggests that a certain level of strength is required for high-level shot put performance but not at the expense of power producing ability.

Recall, bench press ratios for glide shot putters have been shown to be higher than that of rotational athletes (Judge & Bellar, 2012). Performances of athletes using the glide technique have been reported to correlate more with increases in muscular strength measures like a 1RM squat as well. In a study of eight Greek national level glide shot putters, 1RM squat strength was significantly correlated with performance ($r = 0.76$, $p < 0.05$) (Terzis et al., 2007). All the subjects were male with personal best throws ranging between 15.15 and 18.63 m. The researchers did not include measures of muscular power, such as vertical jump, in this study. Overall, the results of these authors and Kyriazis et al. (2009) Greek national shot put studies are in concert with each other, both including a sample of high level performers. Rotational shot put athletes are more likely to rely on muscular power in their legs to accelerate the shot put, whereas glide athletes have the propensity to accelerate the shot put by means of muscular strength. They suggest these differences exist because athletes must accelerate the shot put through the delivery phase much faster using the rotational style than with the glide. Overall, glide and rotational shot putters utilize both strength and power from their legs to help accelerate the shot. Objectively, high levels of strength correlate to performance in the glide technique; whereas, rotational athlete's performance tends to correlate more with measures of power.

Peak Power Output

Apart from 1RM strength and vertical jump, researchers have used other means to assess lower body power of shot put athletes. Researchers measured peak power output (PPO) of the legs and its relation to shot put trials within a sample of shot putters between three to seven years of experience (Landolsi et al., 2014). Researchers measured PPO as leg-force velocity with a cycle ergometer (Monark 894E, Varberg, Sweden), as well as PPO of a vertical jump using the Opto-jump device (Micogate, Bolzano, Italy). In the cycle ergometer test, subjects pedaled a stationary bike where top pedaling speed (velocity) on the ergometer at a certain resistance (force) was used to equate PPO. Researchers found a significant correlation between PPO on the cycle ergometer and shot put performance ($r = 0.72$, $p < 0.001$). While standing between the two Opto-jump system bar sensors, athletes completed a series of vertical jumps utilizing a variety of preceding counter movements. No significant correlation existed between PPO calculated by the Opto-jump device and shot put performance. The researchers attributed the lack of correlation to the onset of anaerobic glycolysis seen during the Opto-jump test, which requires six to eight repetitions of six seconds. The shot put event requires one repetition of two or three seconds and mainly uses Phosphagen reserves (ATP-PC), which were likely depleted midway through the protocol of jumps in this study. In concert with Kyriazis and colleagues' study (2009), it is notable to mention correlations were observed between the actual heights of vertical jumps and shot put performance ($r = 0.51$, $p < 0.05$). The correlations seen between performance and calculated PPO for the cycle ergometer indicate that this may be a valid tool for measuring shot putters, whereas the Opto-jump system is not. Thus, lower body power is crucial to shot put performance as measured by vertical jump height and PPO on a cycle ergometer.

Ballistic Training

Sakamoto et al. (2018) stated power training is characteristic of weight lifting heavy resistances but also speed training with lighter resistances at a high velocity. The researchers used this notion to test whether ballistic bench press training (lightweight Smith Machine barbell thrown and caught), a component of speed training, elicits greater training carryover to shot put performance when compared to standard bench press periodized up to a high intensity. This notion is plausible, because even when an athlete attempts to produce high velocity barbell movements without ballistic action (releasing or jumping with barbell) the latter phases of the movement are spent decelerating the barbell's momentum from the initial concentric acceleration; conversely, ballistic movements like barbell bench press throws or back squat jumps require high velocities of the joints through a greater range of motion (Sakamoto & Sinclair, 2012). The velocities of joints and segments in the ballistic lifts arguably resemble those characteristics of the shot put event. When separating nine male university shot putters into two groups (Personal best throw: bench press non-throw group: 13.86 ± 1.23 m vs. bench press throw group: 13.28 ± 0.96), "Post hoc one-way repeated measures ANOVAs revealed that bench press throw training significantly improved 1RM strength (+ 10.0%, $p < .001$), seated shot put distance (+ 11.7%, $p < .001$) and standing shot put distance (+ 3.8%, $p = .002$) after 12 weeks" (Sakamoto et al., 2018, p.1826). In the study, the bench press non-throw group had no significant improvements of shot put throws. The researchers suggest shot put throw improvements are result of much higher peak angular velocities of the working joints observed in bench press throw trials (1.7 times greater velocity than non-throw, $p < .001$). Although the joint angle velocities during bench press throw trials were slower than those reported in shot put trials (likely due to larger resistance in barbell compared to shot put), the specificity of the movement velocity aligns with shot put performance to a greater degree than traditional bench press technique, thus necessitating its inclusion within shot put power training. The superior improvements in 1RM strength observed within the bench press throw groups were hypothesized to be a result of improvements in stretch shortening cycle improvements, specifically durations of acceleration increased through all the concentric phases of the bench press. Also, greater rates of force production may have also contributed to 1RM improvements, where athletes performing bench press throws eliminated the "sticking region" (deceleration midway through the pressing motion) of the concentric phase common in high intensity traditional bench press (Sakamoto et al., 2018). Overall, ballistic protocols are relevant within power training design for shot put throwers.

Rate of Force Development

The rate of force development (RFD) is a crucial factor for performance in a short duration event like the shot put (150-240ms), and can be understood as muscular ability to produce large amounts of force rapidly (Zaras et. al, 2016). Zaras and colleagues (2016) included this measure in their power field test experiment. Mean tangential slopes were recorded using a force plate (Applied Measurements Ltd Co. UK, WP800, 1000 kg weighting platform, 80 x 80 cm, sampling frequency 1000 Hz) at different time points within a maximal leg press. While correlations were reported between RFD, VL thickness, and VL length, there was no relationship between RFD and throwing event performance increases. Recall though that VL thickness and length increases were significant predictors of increased throwing event performance in the same experiment, so perhaps increased RFD in the leg press would lead to better shot put performance. Using the exact same leg press protocol and RFD calculations, Anousaki et al. (2018) determined that a strong correlation (r = 0.767 – 0.913, p < .05) existed between shot put performance (Female glide shot putter performance at indoor nationals, N = 7, mean performance = 13.90 ± 1.96 m) and lower body RFD at all time increments (100-250ms) and a correlation (r = 0.808 & 0.834, p < .05) between shot put performance and counter-movement jump (CMJ) max and relative power (measured with previously described force plate) as well as maximum force achieved in the leg press (r = 0.766, p < .05). These findings indicate that lower body RFD and power as measured by a CMJ, force plate, and leg press machine can be a useful laboratorybased test for predicting female glide shot put performance. Anousaki and colleagues reported that most notably, RFD during the timing of the final thrust in linear shot put (250ms) had strongest relation to throwing performance (r = .913). Therefore, biomechanically similar contractions are produced during the glide shot put release and latter temporal stages of the leg press test; but this relationship should also be assessed within a sample of rotational throwers (Anousaki et al., 2018).

Electromyography

In addition to muscular strength measures, both Kyrzias et al. (2009) and Terzis et al. (2007) used electromyography (EMG) to measure the Vastus Lateralis (VL) activity of Greek national subjects. EMG surface electrodes (Ag/AgCl) were placed on the VL. The readings were digitized using preamplifiers (TEL100D) with an analog MP100A (Biopac Systems, Inc. Santa Barbara, CA, USA). Average EMG (aEMG) amplitude for VL was calculated in mV for the phases leading up to and including the final release phase. The authors of both studies found a significant relationship for shot put performance and VL activation during the final release phase. These results indicate increased shot put performance is correlated to activation of VL for athletes using both the glide (r =0.91, $p < 0.01$) and rotational (r = 0.81, $p < 0.05$) techniques. In the rotational study, a negative relationship was reported during the phase prior to final release for VL activation and performance (r = -0.75, $p < 0.05$). Recall that rotational shot put is characterized by fluctuating velocities and glide utilizes a more consistent production of velocity. Therefore, the negative relationship for VL activation reported in the rotational study was an indication of a slight decrease in shot put velocity immediately prior to the final release phase. To conclude, VL activation during the final release phase is a crucial for shot put performance of both the rotational and glide techniques.

EMG studies exist where analysis is provided for multiple leg muscles during shot put trials. In a study by Howard et al. (2017), data were collected from 8 males (age 20.9 ± 1.1 years, personal best 11.50 ± 1.43 m) and 7 females (age 20.0 ± 2.4 years, personal best 11.53 ± 1.05 m). EMG sensors were attached to the rectus femoris (RF), biceps femoris (BF), and the medial and lateral gastrocnemius (MG, LG respectively) on both the right and left legs. Muscle activity measurements during the phases of the glide shot put movement were averaged for each gender and compared with regards to timing and duration of activity. The results indicate differences in timing of muscle activity during key phases of the throw across gender, and validates some technical philosophies of coaches not yet proven by EMG research. The study did not look at how these patterns of activity correlate to success. The study only included measurement of eight muscles; the authors suggest future research to include the vastus medialis, vastus lateralis, gluteus maximum, gluteus minimus, soleus and tibialis anterior. Overall, the authors of this study provide data to complement existing kinematic knowledge of the glide technique.

In addition to leg muscles, Terzis et al. (2007) also measured the upper body with EMG. The measurement of pectoralis major (PEC) and triceps brachii (TRI) allowed the researchers to quantify their effect on performance. During final release, the PEC has significant correlation to shot put performance given the measures of aEMG ($r = 0.75$; $p < 0.05$). The authors describe how for all subjects the higher the aEMG of PEC, the further the measured distance. The activation of TRI was determined insignificant in its effect on performance. However, there was a relation reported between performance and the duration of time between preliminary and maximal muscle activity in the TRI during release. Regarding TRI, this means performance is more influenced by the speed of activation than level of activation. This finding may be supported given the results of a study by Tsoukus et al. (2019), where physically active men (n =

10) performing max velocity flat bench press throws (BPT) with lighter (60% of 1RM) resistances showed more TRI activation than that of the lightest condition (40% of 1RM) ($p <$ .001). Therefore, to overcome a heavily resisted implement such as a shot put at high velocity may require higher TRI activation to compliment the action of the PEC. To conclude, emphasis on increased activation level of the PEC should be considered for shot put athletes while speed of activation should be promoted for the TRI.

Recall that both vertical jump performance (Kyrzias et al., 2009), as well as VL thickness, standing long jump, and 40m sprint training improvements (Zaras et al., 2019) have been reported to be significantly associated with increases in shot put performance. Perhaps the results of electromyographic analyses of these power movements may further identify the most significant muscular activation contributors to the shot put movement. For example, in a pilot study of individuals performing maximal vertical jumps, aEMG of quadriceps muscles such as VL and Vastus Medialis (VM) were greater than that of the hamstrings during jumping performance (Greene et al., 2018). This lends EMG based support to the findings of the aforementioned authors' shot put training studies regarding VL thickness and vertical jump being related to shot put performance. According to a meta-analysis by Howard et al. (2018), quadriceps muscles such as the Rectus Femoris (RF) have been shown to achieve the maximal activation during the late swing phase where the leg is extending as the athlete prepares for ground contact. Additionally, higher EMG activations of muscles such as the Biceps Femoris lateral head (BFlh) and have shown to be more useful for propulsive force development during the acceleration phase of sprinting in a sample of male collegiate sprinters (n =13, $p < .05$) (Higashihara et al., 2018). In the same study, Semitendinosus (ST) was shown to be more active than BFlh during maximal speed turnover ($p < .05$). BFlh and ST activations were unstudied components that may have explained some variation in improvements in the 40m dash or shot put throw during Zaras and colleagues (2019)' shot put study; but be significant to sprinting and shot put performance nonetheless. Research regarding muscle activations during standing long jump trials is limited, with authors of one study reporting no significantly different contributions of muscle activations (m. gastrocnemius, m. gluteus maximus, m. rectus femoris, m. tibialis anterior, m. biceps femoris, m. vastus medialis) during standing long jump performance of high caliber male sprinters ($n = 6$) (Mackala et al., 2013).

EMG analysis of the muscular strength movements that researchers have promoted for shot put athlete training may be important to the understanding of throwing performance. Current EMG analyses experiments of power clean, bench press, and back squat movements have not been completed with regard to shot put performance. However, connections can be made between the research implications of different populations and the current discussion. In a study of 10 university aged female volleyball players and 10 university aged male football players, the RF had significantly higher activation within vertical jumps and jump squats when compared to power cleans, $F(2, 38) = 10.6$, $p < .002$ (MacKenzie et al., 2014). In the same study, BF was activated to a significantly greater value during power cleans than during the vertical or squat, jumps, $F(2, 38) = 14.2$, $p < .001$. Therefore, the timing of muscular activation patterns within the lower body during vertical jumps and power cleans differs. Since performance in these two exercises has shown to be correlated to shot put performance (Judge & Bellar, 2012; Kyriazis et al., 2009; Zaras et. al, 2016), efforts of future research should attempt to compare muscle activation patterns consistent between the movements.

Conclusion

In conclusion, elite level performances have been recorded from athletes utilizing both the glide and rotational techniques. Given their differences in technique and phases of movement prior to release, research suggests athletes utilizing the glide and rotational techniques demonstrate different tendencies for accelerating the shot put throughout the movement prior to release. Glide athletes demonstrate a consistent increase of velocity from the start of movement to release, whereas the rotational technique involves some decreases of shot put velocity throughout the movement prior to release. These differences may lead the thrower utilizing a glide technique to be more consistent; however the rotational athlete will have potential for a longer period of force application on the shot put throughout the final phase into release.

The physics of measured distance lends the notion that besides the point of measurement (where athlete is standing when shot put is released; fairly consistent between throwers due to the movement being confined to a 7 foot circle), the projected distance of the throw can be used to determine shot put performance. The projected distance of the throw can be quantified using the projectile motion equation, where angle and velocity of release have the greatest effect on distance. The third factor of the equation, height of release, has less of an effect on the outcome. A tradeoff between angle and velocity of release exists where each athlete individually possesses an optimal angle of release to maximize velocity at the same time. Optimal angle of release for throwers can be considered to be around 41°, with several elite level athletes demonstrating even smaller angular values to maximize horizontal projection of the shot put. However, as a squared value within the projectile motion equation, velocity of release is most impactful to the outcome, and efforts of shot putters should be made in attempt to maximize velocity of release.

The exact kinematic measurement of shot putters in motion has been conducted by researchers using 3-D motion software. One agreed upon finding between several of these research authors is in regards to HRD, where athletes perform better when the shot put is further from the toe board (in the direction of the throw) prior to release. This can be understood as the athlete releasing the shot put out over the toe board as opposed to from a position further back into the ring. Another agreed upon kinematic parameter for shot put success is shoulder-hip separation, where athletes demonstrating positive values (shoulders and chest facing the back of the ring) during the final double support phase create more momentum to accelerate the shot, thus increasing performance. Additionally, a more forward deviation of the chest during the final double support phase may be advantageous given research findings. During release, an acceleration of the shot putter's throwing side paired with a bracing and deceleration of the non-throwing side creates an open-ended kinetic chain for the athlete to accelerate the implement through, and is thus related to increased performance. Finally, a slight increase in the PCOM of the shot put in the flight phase may lead to increase performance through the reciprocal increased loading of the athlete's legs during ground contact and increasing knee extensor force through a stretch shortening event. In this capacity, whether athletes should then attempt to further extend their legs through this ground contact to release is not agreed upon within research studies, with some suggesting a positive relationship with increased extension and others with increased flexion throughout release.

The ability to utilize power to produce rapid body movements in the shot put throw is advantageous. In this capacity, many shot put athletes are tested with power related exercises to monitor abilities. Research studies regarding these power exercises tend to be in agreement with the positive relationship between power production ability and shot put performance. Given the differences in technique, it appears that glide shot put athletes may rely on more muscular strength than rotational athletes, who rely more on muscular power; however this relationship needs to be further explored in research studies.

The patterns and strengths of muscle activations during the shot put throw may be of interest to performance. Using EMG, several research authors have attempted to describe relationships between muscle activations and throwing performance. Results of these research works point to a positive relationship between strength of PEC and VL activation at release and throwing performance, while TRI activation has not yet been demonstrated as significant to performance within research. On the other hand, EMG research for shot putters is limited in regard to analysis of other lower body musculature that has been shown as significant to other powerful movements such as sprinting and jumping (RF, BF, gluteus maximus, vastus medialis, gastrocnemius). More research utilizing muscle activations during the shot put throw should be conducted in order to determine these relationships with more certainty.

References

Anousaki, E, Stasinaki, A. N., Zaras, N., Terzis, G., Methenitis, S., Arnaoutis, G., & Karampatsos, G. (2018). Rate of force development, lean body mass and throwing performance in female shot-put athletes. *Journal of Physical Education and Sport*, *18*, 1699-1703. 10.7752/jpes.2018.03248.

Ariel, G., Penny, A., Probe, J., Rudolf, B., Simonsen, E., Finch, A., & Judge, L. (2004). Biomechanical analysis of the shot-put event at the 2004 athens olympic games. *Ariel Dynamics*. http://www.arielnet.com/pages/show/adi-gba-01359/shotput-2004

Bajrić, O., Biberović, A., Saračević, Z., & Mikić, B. (2017). Influence of angular values of body segments on the distance of the throw out in (Z) axis. *Sports Science and Health, 7*(1),13-21. doi:10.7251/SSH1701013B

Bartonietz, K. (1994) Rotational shot put technique: Biomechanic findings and recommendations for training. *Track and Field Quarterly Review*, *93*(3), 18-29 (1994).

Bartonietz, K. & Borgstrom, A. (1995). The throwing events at the World Championships in Athletics 1995, Goteborg - Technique of the world's best athletes Part 1: Shot put and hammer throw. *New Studies in Athletics*, *10*(4), 43-63.

Burnett, A. (ND). The biomechanics of jumping. *Edith Cowan University Biomechanics. https://elitetrack.com/article_files/biomechanics-of-jumping.pdf*

Byun, K. O., Fujii, H., Murakami, M., Endo, T., Takesako, H., Gomi, K., & Tauchi, K. (2008). A biomechanical analysis of the men's shot put at the 2007 World Championships in Athletics. *New Studies in Athletics*, *23*(2). 53-62. http://www.richwoodstrack.com/rhs_team_area/throws/shot/tech_Biomechanical%20Analysis%20Worlds%202007.pdf

Coh, M. & Stuhec, S. (2005). 3-D kinematic analysis of the rotational shot put technique. *New Studies in Athletics*, *20*(3), 57-66. http://www.richwoodstrack.com/rhs_team_area/throws/shot/tech_Kinematic%20Analysis%20Rotational.pdf

Göksu, Ö. & Kural, D. (2019). Evaluation of the effects of hip joint range of motion and trunk rotation on throwing biomechanics of shot putters: A pilot study. *Acta Medica Mediterranea*, *35*, 2823. 10.19193/0393-6384_2019_5_444.

Greene, J., Wahlund, B., Mittlieder, J., & Lutz, A. (2018). Electromyographic activity of hamstrings and quadriceps muscle during jumping and landing: Pilot study. *Physical Therapy Scholarly Projects, 669*. https://commons.und.edu/pt-grad/669

Harasin, D., Milanović, D. &, Čoh, M. (2010). 3D kinematics of the swing arm in the second double-support phase of rotational shot put- elite vs. sub-elite athletes. *Kinesiology, 42*(2), 169-1774.

Higashihara, A., Nagano, Y., Ono, T., & Fukubayashi, T. (2015). Differences in activation properties of the hamstring muscles during overground sprinting. *Gait & Posture, 42*(3), 360–364.

Howard, R. M., Conway, R., & Harrison, A. J. (2017). Muscle activation sequencing of leg muscles during linear glide shot putting. *Sports Biomechanics*, *16*(4), 463-484. doi:10.1080/14763141.2016.1246601

Hubbard, M., de Mestre, N. J., & Scott, J. (2001). Dependence of release variables in the shot put. *Journal of Biomechanics*, *34*, 449-456. https://pdfs.semanticscholar.org/9fe8/fc595ce6a286b338fba301feb2db04b50f01.pdf

Judge, L. (2012). Spin to win: the rotational shot put. *2012 Iowa State High School Clinic*. https://www.championshipproductions.com/files/tc-02012/Judge-Rotational-Shot-Put-Spin-to-Win.pdf

Judge, L. W. & Bellar, D. (2012). Variables associated with the of personal best performance in the glide and spin shot put for U.S. collegiate throwers. *International Journal of Performance Analysis in Sport, 12*(1), 37-51, DOI:1080/24748668.2012.11868581

Kyriazis, T. A., Terzis, G., Boudolos, K., & Georgiadis, G. (2009). Muscular power, neuromuscular activation, and performance in shot put athletes at preseason and at competition period. *Journal of Strength and Conditioning Research*, *23*(6), 1773-1779. doi: 10.1519/JSC.0b013e3181b3f91e

Landolsi, M., Bouhlel, E., Zarrouk, F., Lacouture, P., & Tabka, Z. (2014). The relationships between leg peak power and shot-put performance in national-level athletes. *Isokinetics & Exercise Science*, *22*(1), 55-61. doi:10.3233/IES-130518

Lanka J., (2000) Shot putting. *Biomechanics in Sport: Performance Improvement and Injury Prevention*. 435–457. https://www.researchgate.net/profile/Arkady_Voloshin/publication/230539546_Impact_Propagation_and_its_Effects_on_the_Human_Body/links/59f8a471a6fdcc075ec990c7/Impact-Propagation-and-its-Effects-on-the-Human-Body.pdf

Linthorne, N. P. (2001). Optimum release angle in the shot put. *Journal of Sports Sciences*, *19*(5), 359-372. DOI: 10.1080/02640410152006135

Mackala, K., Stodolka, J., Siemienski, A. & Coh, M. (2013). Biomechanical analysis of standing long jump from varying starting positions. *Journal of Strength & Conditioning Research, 27*, 2674-2684. https://doi.org/10.1519/JSC.0b013e31825fce65

MacKenzie, S. J., Lavers, R. J., & Wallace, B. B. (2014). A biomechanical comparison of the vertical jump, power clean, and jump squat, *Journal of Sports Sciences, 32*(16), 1576-1585, doi: 10.1080/02640414.2014.908320

Manesh, K., Murali, M., & Dhinu, M. R. (2016). Kinematic analysis of shot release of intercollegiate athletes. *International Journal of Physical Education, Sports and Health. 3*(5), 131-134. http://www.kheljournal.com/archives/2016/vol3issue5/PartC/3-4-73-958.pdf

Pyka, I. & Otrando, (1991). Rotational shot put. *National Strength and Conditioning Association Journal*. *13*(1), 6-9. https://journals.lww.com/nsca-scj/Citation/1991/02000/Rotational_shot_put.1.aspx

Sakamoto, A., Kuroda, A., Sinclair, P., Naito, H., & Sakuma, K. (2018). The effectiveness of bench press training with or without throws on strength and shot put distance of competitive university athletes. *European Journal of Applied Physiology, 118*. 10.1007/s00421-018-3917-9.

Sakamoto, A. & Sinclair, P. J. (2012) Muscle activations under varying lifting speeds and intensities during bench press. *European Journal of Applied Physiology, 112*(3), 1015–1025.

Saračević, Z, Atiković, A., Štuhec, S. S., & Čuk, I. (2018). How kinematics influences shot put results in track and field of international level athletes (a case study). *Journal of Physical Education and Sport, 1*(73), 512-516. DOI:10.7752/jpes.2018.s173

Stander, R. (N.D.). Athletic onimbus- Shot put. http://www.sports-media.be/links/kogelstoten-engelstalig.pdf

Stefanović, R. (2017). Some parameters in crossover phases significant for the result in particular throwing disciplines. *Activities in Physical Education and Sport, 7*(1),13-15.

Stepanek, J. (1989). Comparison of the glide and the rotation technique in the shot put. *Proceedings of the Vth International Symposium of the Society of Biomechanics in Sport. Athens: Hellenic Sport Research Institute, Olympic Sports Centre of Athens*, p. 135–146

Stone, M., Sanborn, K., O'Bryant, H.S., Hartman, M., Stone, M.E., Proulx, C., Ward, B., & Hruby, J. (2003). Maximum strength-power-performance relationships in collegiate throwers. *Journal of Strength and Conditioning Research, 17*(4), 739-45. https://www.semanticscholar.org/paper/Maximum-strength-power-performance-relationships-in-Stone-Sanborn/c52ead4650f83586c35e98e826f41732587bfd7d

Terzis, G., Karampatsos, G., & Georgiadis, G. (2007). Neuromuscular control and performance in shot-put athletes. *Journal of Sports Medicine and Physical Fitness, 47*(3), 284-90. https://ezproxy.lib.ndsu.nodak.edu/login?url=https://search.proquest.com/docview/202676574?accountid=6766

Tsoukos, A., Brown, L. E., Veligekas, P., Terzis, G., & Bogdanis, G. C. (2019). Postactivation potentiation of bench press throw performance using velocity-based conditioning protocols with low and moderate loads. *Journal of Human Kinetics, 68*(1), 81-98. doi: https://doi.org/10.2478/hukin-2019-0058

Young, M. (2004). Critical factors for the shot put. *Track Coach, 166*, 5299-5304. http://www.coachkrall.com/Articles/Shot/shotcriticalfactors.pdf

Young, M. (2009). Development and application of an optimization model for elite level shot putting. *LSU Doctoral Dissertations, 25*. https://digitalcommons.lsu.edu/gradschool_dissertations/25

Young, M. & Li, L., (2005). Determination of critical parameters among elite female shot putters. *Athletics, Sports Biomechanics*, *4*(2), 131-148, DOI: 10.1080/14763140508522859

Zaras, N., Spengos, K., Methenitis, S., Papadopoulos, C., Karampatsos, G., Georgiadis, G., Aggeliki, S., Panagiot, M., & Terzis, G. (2013). Effects of strength vs. ballistic-power training on throwing performance. *Journal of Sports Science & Medicine*, *12*(1), 130–137.

Zaras, N., Stasinaki, A. N, Methenitis, S., Karampatsos, G., Fatouros, I., Hadjicharalambous, M., & Terzis, G. (2019). Track and field throwing performance prediction: Training intervention, muscle architecture adaptations and field tests explosiveness ability. *Journal of Physical Education and Sport, 19*, 436 - 443. 10.7752/jpes.2019.s2064.

Zaras, N. D., Stasinaki, A. N. E., Methenitis, S. K., Krase, A. A., Karampatsos, G. P., Georgiadis, G.V., Spengos, K.M., & Terzis, G.D. (2016). Rate of force development, muscle architecture and performance in young competitive track and field throwers. *Journal of Strength and Conditioning Research, 30*(1), 81-92.

Zatsiorsky, V., Lanka, G. and Shalmanov, A. (1981) Biomechanical analysis of shot putting technique. *Exercise in Sports Science Review*, *9*, 353-389.

CHAPTER 3. MATERIALS & METHODS

Purpose

The first purpose of this investigation was to identify which muscle activations and kinematic positions within the throwing movement, exhibited by the throwers in this sample, had the greatest effect on their throwing performance as measured by their throwing distance. Muscular activity and kinematic relationships were analyzed to determine relationships characteristic of all throwers in the sample, but also to identify any associations that are unique to any singular participant. Additionally, a second purpose of this study was to provide a comparative analysis of glide and rotational techniques to reveal how relationships between distance thrown, muscle activations, and kinematic positions differed for glide and rotational shot put throwers in the sample.

Research Design

The current study follows a correlational research design. There was no manipulation or control of the variables in this study; rather, they were only observed and measured in a natural setting. Once variables were observed, measured, and processed, they were analyzed in attempts to reveal any links between them. The magnitude and direction of these links were determined through statistical processes in order to determine if relationships between variables were positive, negative, or zero. The outcomes of this correlational research investigation provided means to define the real-world circumstances of shot put technique and performance in a legitimate manner.

Procedures

All throwers performed their trials during a one-day experimental session. Two experimental sessions were held in order to accommodate for an analysis of all 12 throwers; both sessions were completed in the first full week of January 2021. Sessions were conducted indoors within an IAAF competition certified shot put ring on the campus of North Dakota State University. Appropriate IAAF approved indoor shot put implements were used by the participants (Men: 7.26kg, Women: 4kg). In order for the motion capture system to track the shot put, it was covered with a thin layer of reflective tape. The distance of each throwing trial was measured in metric units according to IAAF protocol.

EMG and 3D motion analysis data of the shot putters were gathered during this study After a general and a self-selected shot put specific warm up, all throwers were instructed to perform six shot put throws as they would in competition. After the warm up and before the recorded throwing trials, researchers applied motion analysis reflective markers and EMG surface electrodes. The EMG transmitters were fastened with elastic bands. To prevent interference with these technologies, participants were asked to wear compression fitting clothing.

Participants

For this study, the sample consisted of 12 university-level shot put throwers (six males, six females). Informed written consent and permission to use their names was obtained from each participant before testing. If an athlete was injured or for some other reason was not participating in their normal practices, they would not be included in the study. Four of the females utilized a glide technique, the other eight throwers utilized the rotational technique. All participants were right-handed throwers. The shot put throwers who made up this sample are of a high proficiency, as some have received All-American or All-Conference honors in previous competitions (Table 3).

Table 3

Participant Personal Best Throws and Accolades

Sex	Participant	Personal Best Performance (m)	Accolades
Male	Payton Otterdahl	21.81	NCAA D1 Indoor National Champion 2019
	Alex Talley	20.54	NCAA D1 Indoor National 3rd Place 2021
	Kristoffer Thomsen	20.33	NCAA D1 Indoor National 10th Place 2021
	Maxwell Otterdahl	19.66	NCAA D1 Indoor National 8th Place 2021
	Trevor Otterdahl	18.44	
	Clayton Hannula	17.67	
Female	Akealy Moton	18.06	NCAA D1 Indoor National 5th Place 2021
	Shelby Gunnells	17.78	NCAA D1 Indoor National 9th Place 2019
	Tasha Willing	16.08	Summit League All-Conference
	Maggie Schwarzkopf	15.85	Summit League All-Conference
	Maddy Nilles	15.74	Summit League All-Conference
	Amanda Anderson	15.28	

Methods

Vicon Motion Capture

An eight camera Vicon Vantage V5 motion capture system (Vicon Peak, Oxford, UK), capturing at 200 Hz was used to conduct motion capture of the throwing trials. The eight Vicon cameras were affixed to tripods, and positioned in a semi-circle surrounding the shot put ring. A reference camera (60 hz) (Vicon Vue Video Camera) was used to identify each phase of the throwing movement during analysis. For the motion capture analysis, reflective markers with a diameter of 14 mm were placed on specific anatomical landmarks of each participant. The landmarks consisted of the head, C7 and T-12 vertebras, sternum, and from the right and left sides: the acromion process, lateral and medial epicondyles of the humerus, the radial and ulnar heads, anterior superior iliac spine, posterior superior iliac spine, lateral and medial condyles of the femur, the lateral and medial malleolus, the first and fourth metatarsal, and on the posterior aspect of the calcaneus. In addition, clusters of four reflective markers were affixed to each participant's upper and forearms, thighs, and shanks using a neoprene Velcro strap. Three-dimensional data for the markers included displacement as well as relative and absolute angles axes (x, y and z). They were analyzed utilizing Nexus software (Nexus 2.12, Vicon, Oxford, UK). Dependent variables chosen for analysis were: Shoulder-Hip Separation (S-H) using relative trunk rotation in the z axis, absolute Trunk Angle in the x, y, and z planes, and the max height of the pelvis origin during the flight phase, referred to as Peak Center of Mass (PCOM).

EMG

EMG was used to gather the activity of seven different muscles during the shot put trials. The activity of the triceps (TRI), external oblique (EO), latissimus dorsi (LAT), gluteus medius (GLUTE), biceps femoris (BF), rectus femoris (RF), and gastrocnemius (GAS) was gathered from the throwing side of each throwers body. Self-adhesive dual Ag/AgCl snap electrodes (Noraxon, Scottsdale, AZ, USA) (Ag/AgCl) with an interelectrode distance of 2 cm were placed on the muscles according to DeLuca (1997). Electrodes were attached near the muscle belly of each muscle. To improve signal conduction, excess hair was removed with a razor, skin was abraded with rough sponges, and cleaned with alcohol. Reference electrodes were placed on the acromion process and lateral epicondyle of the femur. SENIAM guidelines were used to determine exact placement location of the electrodes (Gullett et al., 2009). The electrodes were attached to a dual channel wireless EMG BioNomadix (BN-EMG2, CMRR > 90 dB) matched transmitter and receiver, interfaced with a Biopac MP-150 (Biopac Inc., Goleta, CA, USA) system.

Data Processing

Marker trajectories were labeled, gap-filled using the spline, pattern, and rigid body fill and trimmed to include the frames of interest. Three-dimensional data for the markers included displacement as well as relative and absolute angles axes (x, y and z), and were analyzed utilizing Nexus software (Nexus 2.12, Vicon, Oxford, UK) and Vicon ProCalc (ProCalc version 1.5, Vicon, Oxford, UK). Relative trunk angles were calculated as euler angles with the distal pelvis segment in reference to the proximal trunk segment, in the order of x, y, z. Additionally, absolute euler angles were defined in reference to the trunk segment and lab coordinate system, also in the order of x, y, z. For the relative trunk angles, z-axis values were used to define trunk rotation; x was defined as flexion and extension; y was defined as lateral flexion. Pelvis origin was established as the midway point between two points that bisect the ASIS and PSIS markers, respectively. For the trunk relative and absolute values, positive values reflect flection, left lateral flexion, right trunk rotation; and negative values reflect extension, right lateral flexion, and left trunk rotation. For PCOM, height in the z direction of the lab coordinate system was used. Model outputs were filtered with a low-pass, zero-lag Butterworth filter (fourth order) at a cutoff frequency of 10 Hz. Kinematic data were exported and combined into Microsoft Excel.

To connect the EMG electrodes, a preamplifier telemetric unit (TEL100D) and an analog to digital conversion unit MP100A (Biopac Systems, Inc. Santa Barbara, CA, USA) were used. EMG signals were recorded at 2 kHz. All EMG data were recorded and analyzed with Acqknowledge 4.4 software (Biopac Inc., Goleta, CA, USA). EMG signals were filtered with a low-high Band Pass filter fixed at 10-450 Hz; all signals were full wave rectified. Finally, signals were filtered with a low pass filter fixed at 8 Hz.

The imitation phase was defined as the movements prior to flight phase; the flight phase was defined as takeoff (start of zero ground contact) to rear foot touch down (RFTD); landing phase was defined as RFTD to front foot touch down (FFTD); and completion was defined as FFTD to release. The high-speed video camera and EMG were synchronized with an external trigger plugged into the Biopac MP100A. Timepoints of specific events (e.g RFTO) were found using the high speed video, and used to identify the corresponding phases in the EMG tracings.

To compare EMG values across participants and trials, signal normalization was necessary. Maximum voluntary isometric contractions are often used to normalize EMG data, but peak EMG values achieved in dynamic trials may be more accurate (Howard et al., 2017). Therefore, peak EMG values achieved by each participant during the trials were used to signify the maximum peak for each muscle. The peak activity of the muscles were also identified within each phase. The peaks in each phase were then divided by the maximum peak value. Thus, values for analysis were all relative to the maximum peak for all trials. The peak EMG values for each phase are reported as a ratio between 0 and 1.0, normalizing the biological variability between individuals.

Statistical Analysis

EMG

For statistical analysis of EMG data, a two-level multi-level modeling approach was used. To analyze common relationships across all of the participants, EMG activations of the seven muscles across the four phases were analyzed. Each thrower's six attempts (Level 1 in the model), were nested within each thrower (Level 2). Statistical analyses were performed using SPSS version 24.0. Statistical significance was defined using $p < 0.05$.

To analyze common relationships across all of the participants, fixed effects of each muscle activation within the four phases were tested. In the analysis, the activation of the seven muscles for each thrower served as covariates in the model, with distance thrown during the trials serving as the dependent variable. In addition, to determine if differences existed between throwers in the relationship between activation within each phase and distance thrown, an analysis of random effects was included.

An interaction term for each muscle activation phase was created to determine whether glide and rotational throwers exhibited different associations between muscle activations and thrown distance. If the fixed effects of a muscle activation variable were significant, coefficients were used to graph the interaction effect and indicate the difference in the direction of the relationship between participants utilizing the two different techniques.

MOCAP

For statistical analysis of MOCAP data, a two-level multi-level modeling approach was used. To analyze common relationships across all of the participants, angular (°) measures were analyzed for the SH Separation, Trunk Angle, and Lateral Trunk Flexion variables and metric distance (cm) measures were analyzed for the PCOM variable within the statistical tests. Each thrower's six attempts (Level 1 in the model), were nested within each thrower (Level 2). Statistical analyses were performed using SPSS version 24.0. Statistical significance was defined using $p < 0.05$.

To analyze common relationships across all of the participants, fixed effects of each variable were tested. In the analysis, the variable measures exhibited by each thrower served as covariates in the model, with distance thrown during the trials serving as the dependent variable.

In addition, to determine if differences existed between throwers in the relationship between these values and distance thrown, an analysis of random effects was included.

An interaction term for each variable was created to determine whether glide and rotational throwers exhibited different associations between variable measures and thrown distance. If the fixed effects of a variable were significant, coefficients were used to graph the interaction effect and indicate the difference in the direction of the relationship between participants utilizing the two different techniques. The same procedure was used to determine whether male and female throwers exhibited different associations between variable measures and thrown distance.

Hypothesis

It is logical to assume relationships exist between distance thrown and some kinematic and EMG values during shot put attempts as well as strength abilities and power abilities. Therefore, these variables were explored within an individual's shot put performances and amongst a sample of different shot put athletes. The first hypothesis was that the magnitude of EMG muscle activations (RF, BF, GAS, TRI, LAT, EO, and GM) during different timepoints of the throwing movement would relate to the measured distance of shot put throws. Likewise, a second hypothesis was that a thrower's body positions (Trunk angle in the X, Y, and Z planes in the landing phase and PCOM in the flight phase) during the throwing movement (measured with MOCAP) would relate to measured distance. The third hypothesis was that the relationships between measured throwing distance and MOCAP or EMG variables, would differ for throwers utilizing the two techniques: glide and rotational.

References

De Luca, C. J. (1997). The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics, 13*, 135–163.

Gullett, J. C., Tillman, M. D., Gutierrez, G. M., and Chow, J. W. (2009). A biomechanical comparison of back and front squats in healthy trained individuals. *Journal of Strength and Conditioning Research, 23*, 284–292.

Howard, R. M., Conway, R., & Harrison, A. J. (2017). Muscle activation sequencing of leg muscles during linear glide shot putting. *Sports Biomechanics*, *16*(4), 463-484. doi:10.1080/14763141.2016.1246601

CHAPTER 4. AN ELECTROMYOGRAPHIC ANALYSIS OF SHOT PUTTERS AT A DIVISION I UNIVERSITY

Introduction

The shot put is a track and field throwing event. Researchers have previously measured athletes performing the shot put throw to determine factors for elite level performances (Ariel et al., 2004; Bartonietz, 1995; Byun et al., 2008). Two techniques for throwing the shot put exist, the glide and rotation. Most competitors begin using the glide technique due to its simplicity (Manesh et al., 2016). The rotational technique may be advantageous for certain athletes, as the period of force application on the shot is longer, which allows the thrower to achieve greater horizontal velocity and carry the shot put a longer distance (Judge, 2012). The rotational and glide techniques can be understood through various phases of movement from start to finish. Although the techniques are different, their phases are somewhat synonymous, consisting of: initiation, flight, landing, and completion phases (Harasin et al., 2010; Howard et al., 2017; Hubbard et al., 2001; Kyriazis et al., 2009; Linthorne, 2001; Manesh et al., 2016; Saračević et al., 2018; Terzis et al., 2007; Young, 2009) (Figure 1).

Electromyography (EMG) is a voltmeter that records voltages within muscle fibers from electrodes placed on the surface of the skin. The recorded depolarizations serve to quantify the strength of contraction (activation) of a muscle (Vigotsky et al., 2018). EMG has been previously used by researchers to measure muscle activations demonstrated by shot put athletes during their throws. However, the number of muscles analyzed within previous shot put EMG studies is limited. During the completion phase, increased shot put performance is correlated to activation of the Vastus Lateralis (VL) for athletes using both the glide (r =0.91, $p < 0.01$) (Terzis et al., 2007) and rotational ($r = 0.81$, $p < 0.05$) (Kyrzias et al., 2009). However, Kyrzias et al. (2009)

reported a negative relationship between VL activation immediately before the delivery phase and shot put performance ($r = 20.75$, $p = 0.05$). In regards to shot put implement velocity throughout the throwing movement, rotational shot put athletes demonstrate fluctuating implement velocities, while glide athletes demonstrate a more consistent increase from start to finish. Thus, the negative relationship for VL activation before the delivery phase found in Kyrzias et al.'s (2009) rotational study may be attributed to the small decrease in shot put velocity prior to the final release phase. Additionally, Terzis et al. (2007) used EMG to measure activations of triceps brachii (TRI) and pectoralis major (PEC). They reported a significant correlation for PEC activation and thrown distance ($r = 0.75$; $p < 0.05$). While the activation of TRI was not significant to performance in Terzi et al. (2007)'s study, a negative relationship existed between performance and longer durations required to achieve maximal TRI activation ($r = -.07$, $p = .05$). Additionally, they discussed the significant relationship found between shot put performance and the percentage of type II muscle fibers in the TRI in previous literature (Terzis et al., 2003). Thus, the authors concluded that shot put performance is more dependent on the rate or speed of TRI activation rather than the level of its activation.

Although not present in the current body of shot put research, activations of muscles other than VL, TRI, and PEC may also impact performance. This notion can be ascertained given the results of EMG research of different movements that consist of similar joint movements (flexion and extension) demonstrated in shot put throwing. Similar to shot put, sprinting includes rapid extensions and flexions of leg joints. For example, in a sample of male collegiate sprinters ($n = 13$), EMG activation of Biceps Femoris lateral head (BFlh) related to propulsive force development during the acceleration phase of the sprinting stride (Higashihara et al., 2018). BFlh is a muscle on the posterior thigh; no published EMG studies examining the hamstring muscles within shot put throws were found. Athlete abilities for movements that involve great power production, such as power cleans and vertical jumps, correlate to shot put performance (Judge & Bellar, 2012; Kyriazis et al., 2009; Zaras et. al, 2016). In a study of college athletes, Rectus Femoris (RF) activity was significantly higher within vertical jumps and jump squats than power cleans, $F(2, 38) = 10.6$, $p < .002$, (MacKenzie et al., 2014). Also, Biceps Femoris (BF) activation was significantly greater within power cleans than the vertical or squat jumps, $F(2, 38) = 14.2$, $p < .001$.

As the current body of research understanding on shot put and EMG is limited, it is necessary to conduct an analysis that includes multiple muscles. The purpose of the current study was to examine EMG activity of seven muscles throughout the four shot put phases within a sample of shot put throwers. It was hypothesized that the magnitude of muscle activation for these seven muscles, within the four different phases, will relate to the thrown distance of the shot put. It was also hypothesized that these relationships will differ for athletes utilizing either the glide or rotational technique.

Participants

The participants consisted of 12 university-level shot put throwers (six males, six females). Informed written consent was obtained from each participant before testing and the methods were approved by the Institutional Review Board. If an athlete was injured or for some other reason was not participating in their normal practices, they were not included in the study. Four of the females utilized a glide technique; the other eight throwers utilized the rotational technique. All participants were right-handed throwers. The shot put throwers that made up this sample are of a high proficiency, as some have received All-American or All-Conference honors in previous competitions at the NCAA Division 1 level.

Methods

For trial recording, participants attended one of two different single-day experimental sessions. Researchers conducted data collections on six different participants per experimental session, both during the first full week of January 2021. An indoor IAAF competition certified shot put ring was used as the setting for sessions, located on the campus of North Dakota State University. Indoor shot put implements used by participants were IAAF approved (Men: 7.26kg, Women: 4kg). IAAF protocol was followed for the measurement of each throwing trial, with measurements being taken from the initial landing point of the shot put to the inside edge of the to board. Thrown distances were measured in metric units.

After a general and a self-selected shot put specific warm up, all throwers were instructed to perform six shot put throws as they would in competition. After the warm up and before the recorded throwing trials, researchers applied EMG surface electrodes, and EMG transmitters fastened with elastic bands. To prevent interference with these technologies, participants were asked to wear compression fitting clothing.

EMG was used to gather the activity of seven different muscles during the shot put trials. The activity of the triceps (TRI), external oblique (EO), latissimus dorsi (LAT), gluteus medius (GLUTE), biceps femoris (BF), rectus femoris (RF), and gastrocnemius (GAS) was gathered from the throwing side of each throwers body. Self-adhesive dual Ag/AgCl snap electrodes (Noraxon, Scottsdale, AZ, USA) (Ag/AgCl) with an interelectrode distance of 2 cm were placed on the muscles according to DeLuca (1997). Electrodes were attached near the muscle belly of each muscle. To improve signal conduction, excess hair was removed with a razor, skin was abraded with rough sponges, and cleaned with alcohol. Reference electrodes were placed on the acromion process and lateral epicondyle of the femur. SENIAM guidelines were used to determine exact placement location of the electrodes (Gullett et al., 2009). The electrodes were attached to a dual channel wireless EMG BioNomadix (BN-EMG2, CMRR > 90 dB) matched transmitter and receiver, interfaced with a Biopac MP-150 (Biopac Inc., Goleta, CA, USA) system.

Data Analysis

To connect the EMG electrodes, a preamplifier telemetric unit (TEL100D) and an analog to digital conversion unit MP100A (Biopac Systems, Inc. Santa Barbara, CA, USA) were used. EMG signals were recorded at 2 kHz. All EMG data were recorded and analyzed with Acqknowledge 4.4 software (Biopac Inc., Goleta, CA, USA). EMG signals were filtered with a low-high Band Pass filter fixed at 10-450 Hz; all signals were full wave rectified. Finally, signals were filtered with a low pass filter fixed at 8 Hz.

The initiation phase was defined as the movements prior to flight phase; the flight phase was defined as takeoff (start of zero ground contact) to rear foot touch down (RFTD); landing phase was defined as RFTD to front foot touch down (FFTD); and completion was defined as FFTD to release. The high-speed video camera and EMG were synchronized with an external trigger plugged into the Biopac MP100A. Timepoints of specific events (e.g RFTO) were found using the high speed video, and used to identify the corresponding phases in the EMG tracings.

To compare EMG values across participants and trials, signal normalization was necessary. Maximum voluntary isometric contractions are often used to normalize EMG data, but peak EMG values achieved in dynamic trials may be more accurate (Howard et al., 2017). Therefore, peak EMG values achieved by each participant during the trials were used to signify the maximum peak for each muscle. The peak activity of the muscles was also identified within each phase. The peaks in each phase were then divided by the maximum peak value. Thus, values for analysis were all relative to the maximum peak for all trials. The peak EMG values for each phase are reported as a ratio between 0 and 1.0, normalizing the biological variability between individuals. Peak EMG values were measured within each phase of the throw (Figure 1).

Statistical Analysis

For statistical analysis of EMG data, a two-level multi-level modeling approach was used. To analyze common relationships across all of the participants, EMG activations of the seven muscles across the four phases were analyzed. Each thrower's six attempts (Level 1 in the model), were nested within each thrower (Level 2). Statistical analyses were performed using SPSS version 24.0. Statistical significance was defined using $p < 0.05$.

To analyze common relationships across all of the participants, fixed effects of each muscle activation within the four phases were tested. In the analysis, the activation of the seven muscles for each thrower served as covariates in the model, with distance thrown during the trials serving as the dependent variable. In addition, to determine if differences existed between throwers in the relationship between activation within each phase and distance thrown, an analysis of random effects was included.

An interaction term for each muscle activation phase was created to determine whether glide and rotational throwers exhibited different associations between muscle activations and thrown distance. If the fixed effects of a muscle activation variable were significant, coefficients were used to graph the interaction effect and indicate the difference in the direction of the relationship between participants utilizing the two different techniques.

Results

In the results below, unstandardized betas are reported. Tests of random effects showed that there were no significant variations across throwers in the relationship between activations of the seven muscles across the four phases and distance thrown. Thus, in the models described below, only the intercept was kept as a random effect. That is, each player had their own intercept but they all shared the same slopes. Descriptive statistical data for the sample are presented in Table 4.

Table 4

Participant Descriptive Data

Sex	Average Distance Thrown	Technique
Female	14.85 ± 1.35m	Glide: n = 4, Rotational: n = 2
Male	17.65 ± 1.49m	Glide: n = 0, Rotational: n = 6

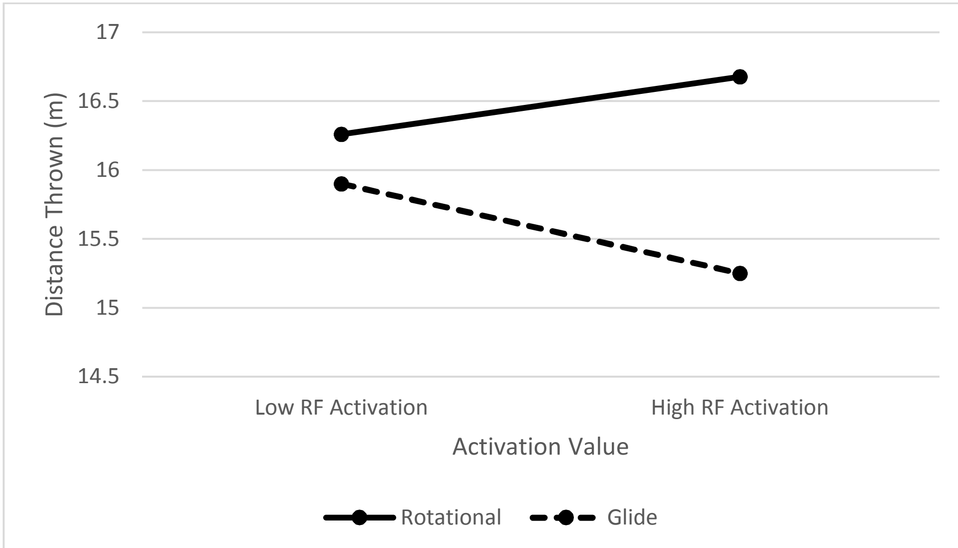
Note. Average distance thrown presented as mean ± standard error.

Initiation Phase

Overall, for each .10 increase in RF activation in the initiation phase, the distance thrown increased by .078 meters (or 7.8 centimeters) (b = .78, p = .032.) Also, during this phase, significant differences existed between the participants using rotational and glide techniques in terms of the relationship between RF activation and thrown distance (b = -1.98, p = .044), as well as for EO, (b = -1.9, p = .002). Specifically, with increasing levels of RF activation in the initiation phase, the distance thrown increased for participants using the rotational technique, and decreased for participants using the glide technique (Figure 8). Similarly, with increasing levels of EO activation in the initiation phase, the distance thrown increased for participants using the rotational technique, and decreased for participants using the glide technique (Figure 9). Initiation phase models including TRI, LAT, GLUTE, BF, and GAS did not reach significance.

Figure 8

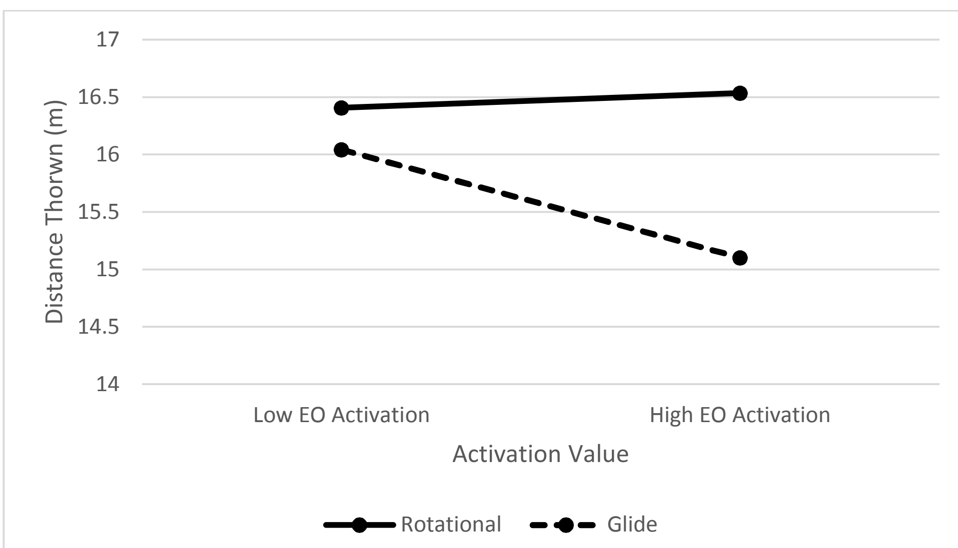
Effects of Technique and RF Activation in Initiation Phase on Distance Thrown



Note: Low RF Activation and High RF Activation were evaluated at one standard deviation below and above the mean, respectively.

Figure 9

Effects of Technique and EO Activation in Initiation Phase on Distance Thrown



Note: Low EO Activation and High EO Activation were evaluated at one standard deviation below and above the mean, respectively.

Flight Phase

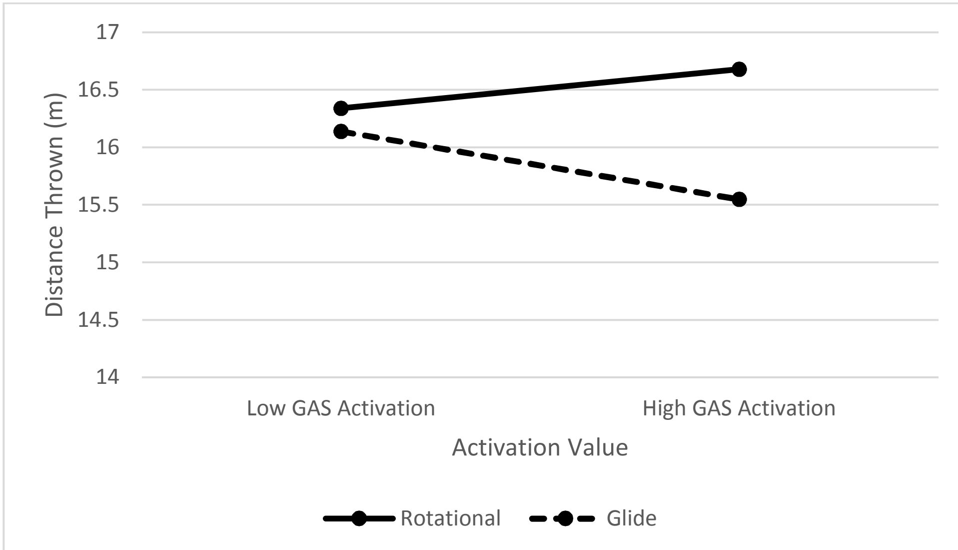
Overall, for each .10 increase in LAT activation in the flight phase, the distance thrown increased by .058 meters (or 5.8 centimeters) (b = .58, p = .042). Also, for each .10 increase in RF activation in the flight phase, the distance thrown increased by .081 meters (or 8.1 centimeters) (b = .81, p = .021). While, for each .10 increase in EO activation in the flight phase, the distance thrown decreased by .124 meters (or 12.4 centimeters) (b = -1.24, p = .005). There were no significant differences in relationships between any muscle activations during this phase and thrown distance for glide and rotational throwers.

Landing Phase

Overall, for each .10 increase in EO activation in the landing phase, the distance thrown decreased by .069 meters (or 6.9 centimeters) (b = -.69, p = .021). During the landing phase, a significant difference existed between the participants using rotational and glide techniques in terms of the relationship between GAS activation and distance thrown (b = -1.66, p = .002). With increasing levels of GAS activation in the landing phase, the distance thrown increased for participants using the rotational technique, and decreased for participants using the glide technique (Figure 10). Landing phase models including TRI, LAT, GLUTE, BF, and RF did not reach significance.

Figure 10

Effects of Technique and GAS Activation in Landing Phase on Distance Thrown



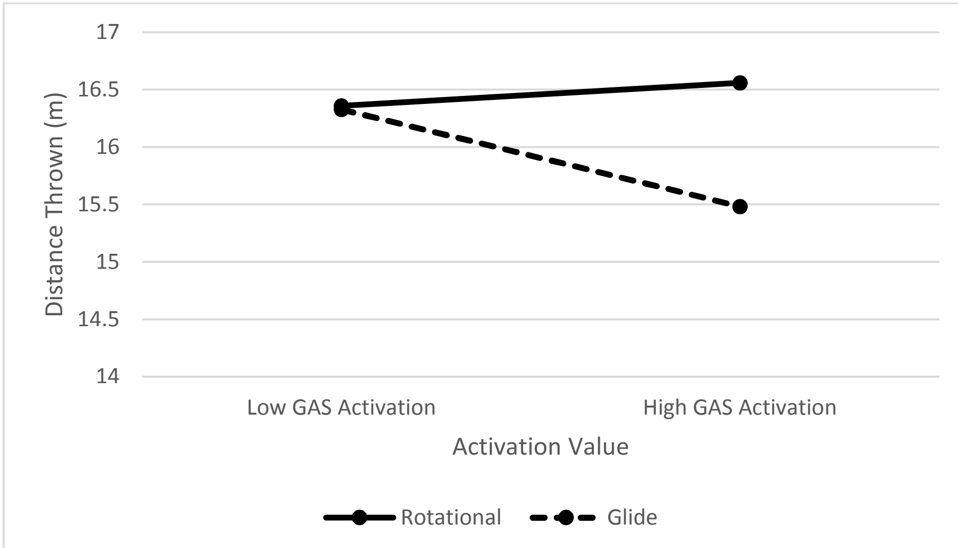
Note: Low GAS Activation and High GAS Activation were evaluated at one standard deviation below and above the mean, respectively.

Completion Phase

Overall, for each .10 increase in LAT activation in the completion phase, the distance thrown increased by .044 meters (or 4.4 centimeters) (b = .44, p = .042). During the completion phase, a significant difference existed between the participants using rotational and glide techniques in terms the relationship between GAS activation and distance thrown (b = -2.01, p = .015). With increasing levels of GAS activation in the completion phase, the distance thrown increased for participants using the rotational technique, and decreased for participants using the glide technique (Figure 11). Completion phase models including TRI, EO, GLUTE, BF, and GAS did not reach significance.

Figure 11

Effects of Technique and GAS Activation in Completion Phase on Distance Thrown



Note: Low GAS Activation and High GAS Activation were evaluated at one standard deviation below and above the mean, respectively.

Discussion

The throwers in this study exhibited a significant relationship between RF activation in the initiation phase and thrown distance, in a positive direction. However, the relationship was different for rotational and glide subjects, as with increasing levels of RF activation in the initiation phase, the distance thrown increased for participants using the rotational technique, and decreased for participants using the glide technique. This may seem contradictory, but the sample consisted of more rotational throwers than gliders, and therefore the trend for rotational throwers was more evident in the overall results of initiation phase muscle activity. The difference observed between RF activation for rotational and glide participants in this study is interesting, as a previous study by Howard et al. (2017) indicated that RF activation is high during this phase for glide shot putters. This difference in findings could be due to the small number of glide shot put throwers available for analysis in the current study. Also, the throwing distance achieved by subjects in Howard et al.'s (2017) was much less (Males: 11.50 ± 1.43 m, Females: 11.53 ± 1.05 m) than throwers in the current study (Table 4).

In the current study, with increasing levels of EO activation in the initiation phase, the distance thrown increased for participants using the rotational technique, and decreased for participants using the glide technique. This is a novel finding, as EO has not been previously analyzed with EMG in shot put research. The differences between the initiation phase movements associated with the two techniques can be used to explain this result. The rotational shot put technique involves torsion of the upper body prior to the initial pivoting leg swing that propels the thrower into the flight phase. In a study of the three medalists competing at (1 glide, 2 rotational) the 2007 men's World shot put final, torsion of the trunk was much greater during the initiation of the throw for the rotational shot putters than the glider (Byun et al., 2008). Perhaps this greater level of trunk torsion exhibited by the rotational athletes in this sample lead to the significantly different effect of EO activation during initiation, as EMG activity of the EO has been shown to be an important factor for trunk torsion movements such as side medicine-ball throws (Ikeda et al., 2009).

In the flight phase, throwers of this sample demonstrated increases in throwing performance with increased activation of LAT and RF. During the flight phase, glide shot putters are achieving a great deal of knee extension, and rotational athletes are to achieve hip flexion during this phase, both of which require RF activation (Murdock et al., 2021). LAT activations have not been studied in previous shot put studies. It is known that LAT activation is required to achieve positions of the upper arm synonymous with arm positions of shot put throwers in this phase: extension and adduction (Jeno & Varacallo, 2021). The associations found between LAT and throwing performance can be explained by the implication that LAT activation would be imperative to keep the shot put supported against the thrower's neck, through extension and adduction of the arm, during the flight phase.

A negative relationship was observed between EO activation during the flight phase and thrown distance. Recall that EO activation during shot put throwing has not been previously researched using EMG. Connections can be drawn from well-studied trunk muscle activations during resistance training movements similar to shot put, such as barbell loaded squatting. As external load increases during back squats, trunk muscle activation also increases (Aspe & Swinton, 2014). During the flight phase, the shot putter's center of mass, plus the mass of the shot put, are accelerating across the ring with instances of zero ground contact. Therefore, the momentum of the athlete and shot put leads to a decrease in the resistance the shot put is exhibiting on the athlete. Similar to back squats, this decreased resistance requires less stabilization through the trunk, which perhaps explains the negative relationship between EO activation in the flight phase and thrown distance within the current study. Superfluous EO activation during the flight phase likely decreases the kinetic energy that the athlete would be able to produce throughout the upcoming concentric work during the landing phase,

Similar to in the flight phase, a negative relationship was observed between EO activation in the landing phase and distance thrown. Researchers have found trunk stabilizer muscles such as EO to be less active during eccentric portions of a back squat movement than during the concentric portion (Clark et al., 2021). The landing phase of the shot put movement consist of an eccentric loading of the dominant leg. Therefore, similar to the back squat, perhaps the eccentric nature of the landing phase during shot put is characterized by less EO activity. Thus, excess activation of EO during the landing phase is unnecessary and lead to a decrease in thrown distance in the current study.

There was a difference in the relationship between GAS activation in the landing phase and thrown distance for participants using the rotational and glide techniques in the current study. That being, as GAS activation increased, thrown distance increased for rotational throwers and decreased for glide throwers. The same difference existed in the relationship between GAS activation and thrown distance in the completion phase. Kinematic differences between the two techniques may explain this finding. Although no relationships have been found in previous research regarding ankle angle differences of glide and rotational shot putters, the athletes utilizing the rotational technique may have been in a more plantar flexed ankle position, which under load, would elicit more GAS activity (Paz et al., 2021). It can be assumed that throws coaches would direct athletes to maintain as much plantarflexion as possible in the landing phase, as it would be necessary for maximal distal-proximal sequencing of leg muscle activation. Therefore, perhaps the glide athletes in the current sample might benefit from further development of the calf muscles through resistance training. Recent literature indicates loaded calf raise abilities are useful in the improvements of sprinting (Möck et al., 2018) and drop jumps (Keiner et al., 2021).

Finally, the throwers in this study exhibited a significant relationship between LAT activation in the completion phase and thrown distance, in a positive direction. During the completion phase, the pectoralis major (PEC) serves as a protagonist muscle for the thrower to release the shot put (Terzis & Karampatsos, 2007). PEC also serves a prime mover during barbell pressing exercises (Rocha Júnior, 2007; Terzis & Karampatsos, 2007). Such forceful activations of the PEC during the shot put release will also require LAT activation. Anatomically, the LAT works with PEC and teres major to adduct, medially rotate, and extend the humerus; said motions are achieved within the shot put release (Jeno & Varacallo, 2021).

Results from previous EMG investigations of the LAT during flat barbell bench press (Król et al., 2010) and pushups (Lehman et al., 2006) indicate its contribution is small. However, LAT activation is greater with barbell overhead pressing movements, and increases in unstable conditions, such as with a barbell affixed with kettlebells using resistance bands (Williams et al., 2020). Perhaps the unstable and overhead nature of the shot put release motion during the completion of the throw explains the association between LAT activation and shot put performance.

Conclusion

This study included a multiple-muscle EMG analysis of the shot put movement. As a result, an explanation of the relationships between muscle activation and shot put performance have been extended. The findings of this study have expanded the body of literature pertaining to shot put and EMG, particularly in the analysis of EO, GM, and LAT, as their inclusions outside of the current study have not been found.

For athletes utilizing either the rotational or glide technique, RF activation in the flight phase appears to have the greatest effect on maximizing thrown distance. On the other hand, EO activation in the flight phase negatively affected performance to a great degree. Activation of EO in the landing also negatively related to performance. Additionally, throwers of both techniques achieved greater distances with increased activations of RF in the initiation phase and LAT in the flight phase. Similarly, increased activation of LAT during the completion phase positively affected performance.

This study exposed the differing relationship between muscle activations and performance for glide and rotational shot put throwers. It was found that increased activations of RF and EO during initiation was favorable for rotational throwers but not glide. Similarly, rotational throwers benefited from increased activation of GAS in the landing and completion phases, while the glide throwers did not.

There were some limitations in the current study, as trials were conducted in a practice setting, and the nuances of a competition setting were not fully replicated. Additionally, the EMG electrodes and units were adhered and strapped to the thrower's body, which may have impeded natural throwing technique, as well as prolonged the time between warm-up and throwing while EMG equipment was being affixed. The timing of the data collection should also be considered. The participants were college students, and had just returned from a three-week long semester break from coach-supervised shot put training.

From this study, there is now evidence as to which muscles are activated throughout the rotational and glide shot put movement. The data from this study can be used by coaches to confirm or re-assess the way in which they educate their athletes regarding shot put technique. It can also be used to plan both technical and strength and conditioning aspects of annual training. Researchers now have additional information to enhance their understanding of muscle activations during shot put. Future research should be conducted on the muscles included in this study, as several have not been found within previous shot put EMG studies. Additionally, resistance training measurements could be included as a variable within shot put and EMG studies to see if any relationships exist between strength and power abilities of shot putters, muscle activations during their throw, and the distances achieved.

References

Aspe, R. R. & Swinton, P. A. (2014). Electromyographic and kinetic comparison of the back squat and overhead squat. *Journal of Strength and Conditioning Research*, *28*(10), 2827-2836. doi: 10.1519/JSC.0000000000000462

Ariel, G., Penny, A., Probe, J., Rudolf, B., Simonsen, E., Finch, A., & Judge, L. (2004). Biomechanical analysis of the shot-put event at the 2004 athens olympic games. *Ariel Dynamics*. http://www.arielnet.com/pages/show/adi-gba-01359/shotput-2004

Bartonietz, K. & Borgstrom, A. (1995). The throwing events at the World Championships in Athletics 1995, Goteborg - Technique of the world's best athletes Part 1: Shot put and hammer throw. *New Studies in Athletics*, *10*(4), 43-63.

Byun, K. O., Fujii, H., Murakami, M., Endo, T., Takesako, H., Gomi, K., & Tauchi, K. (2008). A biomechanical analysis of the men's shot put at the 2007 World Championships in Athletics. *New Studies in Athletics*, *23*(2). 53-62. http://www.richwoodstrack.com/rhs_team_area/throws/shot/tech_Biomechanical%20Analysis%20Worlds%202007.pdf

Clark, D.R., Lambert, M.I., Grigson, C., & Hunter, A. M. (2021). Impact of resistance training status on trunk muscle activation in a fatiguing set of heavy back squats. *European Journal of Applied Physiology, 121*, 597–608. https://doi.org/10.1007/s00421-020-04540-0

Harasin, D., Milanović, D. &, Čoh, M. (2010). 3D kinematics of the swing arm in the second double-support phase of rotational shot put- elite vs. sub-elite athletes. *Kinesiology, 42*(2), 169-1774.

Howard, R. M., Conway, R., & Harrison, A. J. (2017). Muscle activation sequencing of leg muscles during linear glide shot putting. *Sports Biomechanics*, *16*(4), 463-484. doi:10.1080/14763141.2016.1246601

Hubbard, M., de Mestre, N. J., & Scott, J. (2001). Dependence of release variables in the shot put. *Journal of Biomechanics*, *34*, 449-456. https://pdfs.semanticscholar.org/9fe8/fc595ce6a286b338fba301feb2db04b50f01.pdf

Higashihara, A., Nagano, Y., Ono, T., & Fukubayashi, T. (2015). Differences in activation properties of the hamstring muscles during overground sprinting. *Gait & Posture, 42*(3), 360–364.

Ikeda, Y., Miyatsuji, K., Kawabata, K., Fuchimoto, T., & Ito, A. (2009). Analysis of trunk muscle activity in the side medicine-ball throw. *The Journal of Strength & Conditioning Research*, *23*(8), 2231-2240.

Jeno S. H. & Varacallo, M. (2021). Anatomy, back, latissimus Dorsi. In: *StatPearls* (Internet). StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK448120/

Judge, L. (2012). Spin to win: the rotational shot put. *2012 Iowa State High School Clinic*. https://www.championshipproductions.com/files/tc-02012/Judge-Rotational-Shot-Put-Spin-to-Win.pdf

Judge, L. W. & Bellar, D. (2012). Variables associated with the of personal best performance in the glide and spin shot put for U.S. collegiate throwers. *International Journal of Performance Analysis in Sport, 12*(1), 37-51, DOI:1080/24748668.2012.11868581

Keiner, M., Kadlubowski, B., Hartmann, H., & Wirth, K. (2021). The influence of maximum strength performance in squats and standing calf raises on squat jumps, drop jumps, and linear as well as change of direction sprint performance in youth soccer players. *International Journal of Sports and Exercise Medicine*, *7*, 190.

Król, H., Golas, A., & Sobota, G. (2010). Complex analysis of movement in evaluation of flat bench press performance. *Acta of Bioengineering and Biomechanics, 12*(2), 93-97. http://www.actabio.pwr.wroc.pl/Vol12No2/10.pdf

Kyriazis, T. A., Terzis, G., Boudolos, K., & Georgiadis, G. (2009). Muscular power, neuromuscular activation, and performance in shot put athletes at preseason and at competition period. *Journal of Strength and Conditioning Research*, *23*(6), 1773-1779. doi: 10.1519/JSC.0b013e3181b3f91e

Lehman, G. J., MacMillan, B., MacIntyre, I., Chivers, M., & Fluter, M. (2006). Shoulder muscle EMG activity during push up variations on and off a Swiss ball. *Dynamic Medicine, 5*(7). https://doi.org/10.1186/1476-5918-5-7

Linthorne, N. P. (2001). Optimum release angle in the shot put. *Journal of Sports Sciences*, *19*(5), 359-372. DOI: 10.1080/02640410152006135

MacKenzie, S. J., Lavers, R. J., & Wallace, B. B. (2014). A biomechanical comparison of the vertical jump, power clean, and jump squat, *Journal of Sports Sciences, 32*(16), 1576-1585, doi: 10.1080/02640414.2014.908320

Manesh, K., Murali, M., & Dhinu, M. R. (2016). Kinematic analysis of shot release of intercollegiate athletes. *International Journal of Physical Education, Sports and Health. 3*(5), 131-134. http://www.kheljournal.com/archives/2016/vol3issue5/PartC/3-4-73-958.pdf

Möck, S., Hartmann, R., Wirth, K., Rosenkranz, G., & Mickel, C. (2018). Correlation of dynamic strength in the standing calf raise with sprinting performance in consecutive sections up to 30 meters. *Research in Sports Medicine*, *26*(4), 474-481.

Murdock, C. J., Mudreac, A., & Agyeman, K. (2021) Anatomy, abdomen and pelvis, rectus femoris muscle. In: *StatPearls* [Internet]. StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK539897/

Paz, G. A., Maia, M., Castro, J., de Oliveira, F., Miranda, H., Lima, V. P., & Willardson, J. M. (2021). Myoelectric activity of the gastrocnemius during plantar flexion in a standing versus seated position and with a neutral or dorsiflexed ankle: A pilot study. *Journal of Bodywork and Movement Therapies, 26*, 406-410. https://doi.org/10.1016/j.jbmt.2020.09.003.

Rocha Júnior, V. D. A., Gentil, P., Oliveira, E., & Carmo, J. D. (2007). Comparison among the EMG activity of the pectoralis major, anterior deltoidis and triceps brachii during the bench press and peck deck exercises. *Revista Brasileira de Medicina do Esporte*, *13*, 51-54.

Saračević, Z, Atiković, A., Štuhec, S. S., & Čuk, I. (2018). How kinematics influences shot put results in track and field of international level athletes (a case study). *Journal of Physical Education and Sport, 1*(73), 512-516. DOI:10.7752/jpes.2018.s173

Terzis, G., Georgiadis, G., Vassiliadou, E., & Manta, P. (2003). Relationship between shot put performance and triceps brachii fiber type composition and power production. *European journal of applied physiology*, *90*(1-2), 10–15. https://doi.org/10.1007/s00421-003-0847-x

Terzis, G., Karampatsos, G., & Georgiadis, G. (2007). Neuromuscular control and performance in shot-put athletes. *Journal of Sports Medicine and Physical Fitness, 47*(3), 284-90. https://ezproxy.lib.ndsu.nodak.edu/login?url=https://search.proquest.com/docview/202676574?accountid=6766

Vigotsky A. D., Halperin, I, Lehman, G. J., Trajano, G. S., & Vieira, T.M. (2018). Interpreting signal amplitudes in surface electromyography studies in sport and rehabilitation sciences. *Frontiers in Physiology, 8*. DOI:10.3389/fphys.2017.00985

Williams Jr, M. R., Hendricks, D. S., Dannen, M. J., Arnold, A. M., & Lawrence, M. A. (2020). Activity of shoulder stabilizers and prime movers during an unstable overhead press. *The Journal of Strength & Conditioning Research*, *34*(1), 73-78.

Young, M. (2009). Development and application of an optimization model for elite level shot putting. *LSU Doctoral Dissertations, 25*. https://digitalcommons.lsu.edu/gradschool_dissertations/25

Zaras, N. D., Stasinaki, A. N. E., Methenitis, S. K., Krase, A. A., Karampatsos, G. P., Georgiadis, G.V., Spengos, K.M., & Terzis, G.D. (2016). Rate of force development, muscle architecture and performance in young competitive track and field throwers. *Journal of Strength and Conditioning Research, 30*(1), 81-92.

CHAPTER 5. A KINEMATIC ANALYSIS OF SHOT PUTTERS AT A DIVISION I UNIVERSITY

Introduction

The movement technique for throwing shot put is very complex, and is confined to a very small area. For a throw to be considered legal, the shot putter must stay within the confines of a 7 foot diameter circle during the movement and the shot put must land within the area of the sector. Determining the success of a shot put attempt is rather simple, given the measured distance of the throw being the main criteria. Many researchers agree that release conditions such as velocity, angle, and height of release are direct determinants for quantifying the resultant distance of the shot put throw (Hubbard, 2001; Linthorne, 2001; Young, 2009). However, the release occurs at the end of the complex shot put movement. The most valuable information for coaches is in the pursuit of improving the movement technique to optimize the release metrics. To optimize release parameters, a thrower must demonstrate specific positions of the body and limbs at each phase of the movement leading up to release

Kinematic analysis is used to analyze linear and angular displacements of movements in relation to the environment by using identified markers placed on anatomical landmarks of an athlete. Various technologies are utilized to conduct kinematic analyses, including 2-Dimensional video analysis and 3-Dimensional motion capture (MOCAP). MOCAP analysis has been used to test positions, velocities, and accelerations of a shot putter's body/body segments in order to determine which parameters are most important to achieve longer throw (Bajrić et al., 2017; Bartoneitz & Borgstrom, 1995; Manesh et al., 2016; Saračević et al., 2018; Young, 2009). The researchers of these studies lend some practical results for coaches to regard in their attempts to understand optimal shot put technique.

Shot put athletes utilize either a glide or rotational movement to produce maximal velocity of the shot put at release. The glide and rotational shot put movements can be compartmentalized into four distinct phases for kinematic analysis (Figure 1). The four phases consist of: initiation, flight, landing, and completion. The most significant findings of kinematic shot put studies have been found within the flight, landing, and completion phases of the shot put movement. In the flight phase, greater peak height of center of mass during the flight phase (PCOM) (vertical displacement values of the athlete plus-shot system) was a strong predictor of greater measured distance (Young, 2009). During the landing phase, greater knee flexion at rear foot touchdown has been shown to positively effect performance (Young, 2009); the amount of trunk inclination during landing also appears to be related to performance (Bajrić et al., 2017). At the point of release, neutral shoulder hip (S-H) separation and greater horizontal release distance (distance shot put is released past the toe board) predicted greater measured distance (Young, 2004; Young, 2009). In a study that analyzed throwing kinematics and trunk range-of-motion, shot put throwers who exhibited greater goniometer measured abilities of lateral trunk flexion in the direction of the dominant side achieved greater thrown distances (Göksu & Kural, 2019).

Shot put throwers produce a majority of shot put acceleration in the landing phase (Stander, N.D.). Therefore, the landing position, commonly referred to by coaches as the power position, is of significant importance to performance. Landing phase kinematics have been analyzed previously, but further examination is required in order to provide coaches with the greatest understanding as to how intricacies of the landing position might affect performance. In the current study, an analysis of some previously studied landing position kinematics was explored: S-H separation and angle of trunk inclination; lateral trunk flexion exhibited in the landing position was also quantified. Although not part of the landing position, PCOM during the flight phase was analyzed within the current study given its inclusion in a previous research investigation. It was hypothesized that the aforementioned landing position and flight phase kinematics will relate to thrown distance of the shot put. It was hypothesized that these relationships will differ between athletes utilizing glide and rotational techniques, as well as between males and females.

Participants

The participants were 12 university-level shot put throwers (six males, six females). Each participant completed written consent before testing. Individuals were not included in the study if they were injured or not participating in regularly scheduled practices at the time of data collection. None of the males utilized a glide technique, and four of the females utilized a glide technique; therefore the sample consisted of four gliders and eight rotators. All participants threw the shot put with their right hand. Many of the shot putters in this sample have received All-American or All-Conference honors in previous competitions, and therefore can be considered highly proficient.

Methods

The methods of this study were approved by the North Dakota State University Institutional Review Board (IRB). Informed written consent was obtained from each participant before testing. Each athlete participated in a one-day experimental session for recording of trials. To accommodate for an analysis of all throwers, two experimental sessions were held. Both sessions were conducted during the first full week of January 2021. Sessions were conducted within an IAAF competition certified indoor shot put ring on the North Dakota State University campus. Participants used appropriate IAAF approved indoor shot put implements (Men: 7.26kg, Women: 4kg) for throwing trials. Thrown distances were measured according to IAAF protocol using metric units.

All throwers were instructed to perform a self-selected shot put specific warm-up. Immediately following the warm up, researchers applied reflective markers to specific anatomical landmarks for kinematic analysis. Participants were asked ahead-of-time to wear compression fitting clothing to the experimental session, preventing interference of reflective markers. After markers were applied, participants were instructed to take six throws for measurement, just as they would in competition.

An eight camera Vicon Vantage V5 motion capture system (Vicon Peak, Oxford, UK), capturing at 200 Hz was used to conduct motion capture of the throwing trials. The eight Vicon cameras were affixed to tripods, and positioned in a semi-circle surrounding the shot put ring. A reference camera (60 hz) (Vicon Vue Video Camera) was used to identify each phase of the throwing movement during analysis. For the motion capture analysis, reflective markers with a diameter of 14 mm were placed on specific anatomical landmarks of each participant. The landmarks consisted of the C7 and T-12 vertebras, sternum, and from the right and left sides: the acromion process, lateral and medial epicondyles of the humerus, the radial and ulnar heads, anterior superior iliac spine, posterior superior iliac spine, lateral and medial condyles of the femur, the lateral and medial malleolus, the first and fourth metatarsal, and on the posterior aspect of the calcaneus. In addition, clusters of four reflective markers were affixed to each participant's upper and forearms, thighs, shanks, and head using a neoprene Velcro strap.

Three-dimensional data for the markers included displacement as well as relative and absolute angles axe (x, y and z). They were analyzed utilizing Nexus software (Nexus 2.12, Vicon, Oxford, UK). Independent variables chosen for analysis were: Shoulder-Hip Separation

(S-H) using relative trunk rotation in the z axis, absolute Trunk Angle in the x, y, and z planes, and the max height of the pelvis origin during the flight phase, referred to as Peak Center of Mass (PCOM). See Table 5 for a description of these variables.

Table 5

Terminology

Trunk Angle	The angle of trunk inclination corresponding to the horizontal plane. Measured at the start of the landing phase (FFTD).
S-H Separation	The orientation of the shoulders relative to the orientation of the hips. Measured at the start of the landing phase (FFTD).
Trunk Lateral Flexion	The lateral inclination of the trunk. Lateral flexion towards the throwing arm side of the body is defined as more trunk lateral flexion. Measured at the start of the landing phase (FFTD).
PCOM	The highest value of vertical displacement of the thrower's center of mass during the flight phase.

Note: FFTD- front foot touch-down

Data Analysis

Marker trajectories were labeled, gap-filled using the spline, pattern, and rigid body fill and trimmed to include the frames of interest. Three-dimensional data for the markers included displacement as well as relative and absolute angles with respect to each axis (x, y and z). They were analyzed utilizing Nexus software (Nexus 2.12, Vicon, Oxford, UK) and Vicon ProCalc (ProCalc version 1.5, Vicon, Oxford, UK). Relative trunk angles were calculated as euler angles with the distal pelvis segment in reference to the proximal trunk segment, in the order of x, y, z. Additionally, absolute euler angles were defined in reference to the trunk segment and lab coordinate system, also in the order of x, y, z. For the relative trunk angles, z-axis values were used to define trunk rotation; x was defined as flexion and extension; y was defined as lateral flexion. The pelvis origin was established as the midway point between two points that bisect the ASIS and PSIS markers, respectively. For the trunk relative and absolute values, positive values reflect flexion, left lateral flexion, right trunk rotation; and negative values reflect extension, right lateral flexion, and left trunk rotation. For PCOM, height in the z direction of the lab coordinate system was used. Model outputs were filtered with a low-pass, zero-lag Butterworth filter (fourth order) at a cutoff frequency of 10 Hz. Kinematic data were exported and combined into Microsoft Excel.

Statistical Analysis

For statistical analysis of MOCAP data, a two-level multi-level modeling approach was used. To analyze common relationships across all of the participants, angular (°) measures were analyzed for the SH Separation, Trunk Angle, and Lateral Trunk Flexion variables and metric distance (cm) measures were analyzed for the PCOM variable within the statistical tests. Each thrower's six attempts (Level 1 in the model), were nested within each thrower (Level 2). Statistical analyses were performed using SPSS version 24.0. Statistical significance was defined using $p < 0.05$.

To analyze common relationships across all of the participants, fixed effects of each variable were tested. In the analysis, the variable measures exhibited by each thrower served as covariates in the model, with distance thrown during the trials serving as the dependent variable. In addition, to determine if differences existed between throwers in the relationship between these values and distance thrown, an analysis of random effects was included.

An interaction term for each variable was created to determine whether glide and rotational throwers exhibited different associations between variable measures and thrown distance. If the fixed effects of a variable were significant, coefficients were used to graph the interaction effect and indicate the difference in the direction of the relationship between participants utilizing the two different techniques. The same procedure was used to determine whether male and female throwers exhibited different associations between variable measures and thrown distance.

Results

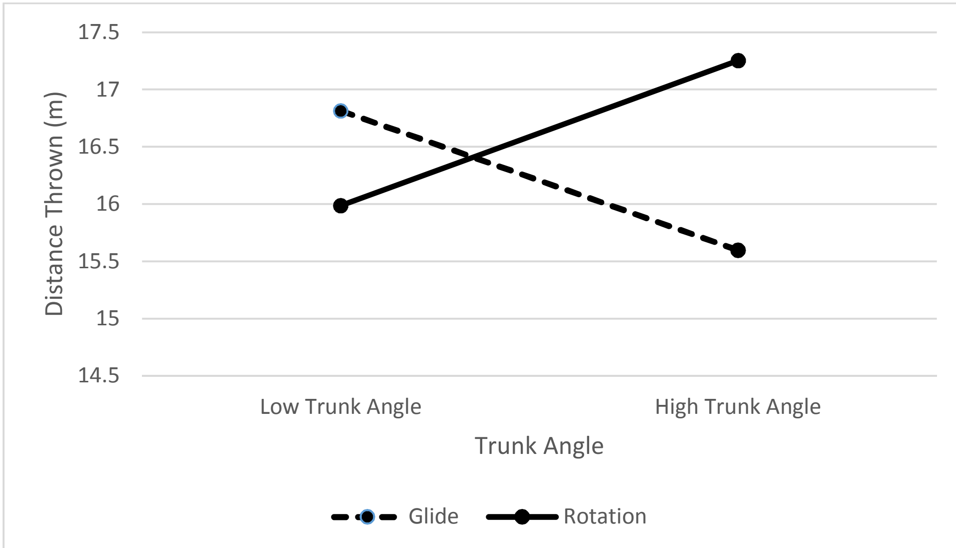
In the results below, unstandardized betas are reported. Tests of fixed effects showed that there were no significant main effects of any of the variables tested and distance thrown. Additionally, tests of random effects showed that there were no significant variations across throwers in the relationship between variable measures and distance thrown. In the models described below, only the intercept was kept as a random effect. That is, each player had their own intercept but they all shared the same slopes. Descriptive statistical data for the sample can be found in the previous chapter (Table 4).

Trunk Angle

Marginally significant differences existed between the participants using rotational and glide techniques in terms of the relationship between trunk angle values and thrown distance ($b = .102$, $p = .056$). Specifically, as angles of trunk inclination were less acute and closer to 90°, the distance thrown increased for participants using the rotational technique, and decreased for participants using the glide technique (Figure 12).

Figure 12

Effects of Technique and Trunk Angle on Distance Thrown



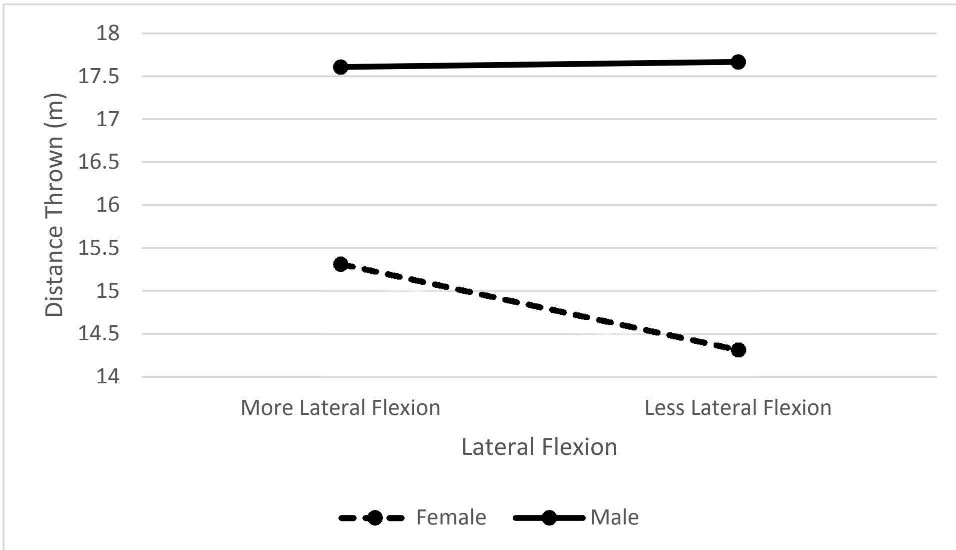
Note: Low Trunk Angle and High Trunk Angle were evaluated at one standard deviation below and above the mean, respectively. Trunk angles were measured from the horizontal plane.

Lateral Trunk Flexion

Within the analysis including trunk lateral flexion and the interaction term based on sex, males threw further than females by 3.69m (b = 3.690, p < .001) when trunk lateral flexion was zero. Additionally, for every 1° change in lateral trunk flexion towards the thrower's non-throwing side (less lateral flexion), the distance thrown decreased by 5.4 cm for females (b = -.054, p = .022). For males, every 1° change in lateral trunk flexion towards the thrower's non-throwing side resulted in a .6cm increase in distance thrown. Marginally significant differences existed between the male and female participants in terms of the relationship between lateral trunk flexion angles and thrown distance (b = .060, p = .088). Specifically, as lateral trunk flexion towards the throwing side of the body decreased, the distance thrown was relatively stable for male participants and decreased for female participants (Figure 13).

Figure 13

Effects of Sex and Lateral Trunk Flexion on Distance Thrown



Note: More Lateral Flexion) and Less Lateral Flexion (towards throwing side) were evaluated at one standard deviation below and above the mean, respectively.

Discussion

It is suggested that trunk angle and shoulder axis determine the length of the shot put acceleration path, but this concept is not definitively supported by empirical data (Schofield et al., 2022). In the current study, the effects of trunk angle during the landing phase were marginally different for throwers using the rotational or glide technique. Rotational athletes threw further when demonstrating a more upright torso, while glide athletes recorded shorter thrown distances as the torso became more upright. This finding furthers the understanding of trunk angle in shot put research, as previous research on female shot put throws utilizing both glide and rotational techniques indicated no significant effects of trunk angle (Young, 2009). In a case study of the three medalists' (1 glide, 2 rotational) top throw from the 2007 men's World shot put final, researchers indicate the finalists all exhibited a deep forward leaning angle of the trunk as they entered the landing position (Byun et al., 2008). The glide shot putter from the study demonstrated more forward lean in the landing position, while the rotational throwers were more upright. This result may compliment the findings of the current study, where gliders did not throw as far when their torso was upright. However, the study of Olympic medalists was a case study, and results were not confirmed to significantly relate to performance through the statistical analysis of multiple attempts. Researchers who completed an analysis of 85 shot put trials of one elite male rotational shot putter (personal best: 20.73m) reported a relationship between trunk angles (z-axis angular values at the L5 lumbar vertebra and S1 sacral region, at 0.1 seconds before release) and further measured distances of throws (Bajrić et al., 2017). While this relationship was found to be significant, it is unclear in the publication if their results were in concert with the current study.

Less lateral trunk flexion produced a marginally significant decrease in throwing distance for women in this study. Thus, females threw further when exhibiting more lateral flexion towards the throwing side. Measuring landing phase trunk lateral flexion of a shot put thrower is a novel idea, previous kinematic studies using this variable for analysis have not been found. However, in a study by Göksu and Kural (2019), researchers performed goniometric measurements of hip and trunk movements on a sample of shot put throwers. They reported a strong positive correlation (r = .72) between dominant side lateral trunk flexion and distance thrown for females. Thus, the results of the current study are in concert with Göksu and Kural's findings. In their study, trunk lateral flexion towards the non-throwing side negatively correlated to angle of release (r = -.89). Meaning that as those who achieved greater non-throwing side lateral flexion in goniometric measurements, release angles decreased. While it has been established that a release angle of 41° or less is optimal (Ariel et al., 2004; Linthorne, 2001), perhaps the negative relationship observed between less lateral trunk flexion and thrown distance in the current study is due to the subsequent increase in release angle resulting from that lateral flexion.

Conclusion

This study used MOCAP technology to provide a kinematic analysis of the shot put movement. As a result, the effects of flight and landing position kinematics on shot put performance have been extended. The results of this investigation add to the body of literature pertaining to shot put kinematics, particularly in the analysis of lateral trunk flexion at the landing position, as its inclusions outside of the current study has not been found. The results also broaden the understanding of previously studied kinematic positions in the flight and landing phases.

The landing position, or power position, should be optimized by shot put throwers, because much of the shot put acceleration occurs during the landing phase. In the current study, participants utilizing the rotational shot put technique threw further as their trunk angle became more upright in the landing position. The opposite was true for gliders, who threw better with more acute angles of the trunk at landing. In regards to lateral flexion of the trunk in the landing position, females threw further with more lateral flexion towards their throwing side.

The current study was not without limitations. The competition setting was not fully replicated for data collection sessions, as trials were performed within a practice setting. MOCAP reflective markers and clusters were affixed to the participant's bodies with adhesive and Velcro straps, which may have impeded their throwing motion. The time taken to affix the markers and cluster is also a limitation, causing the time between warm-up and throwing to be longer than usual practice or competition sessions. Finally, the data collections were conducted in early January, a time where participants were returning from semester break. Therefore, they had not partaken in coach-supervised shot put throwing for 3-weeks prior to data collection.

The findings of this study are practical to track and field coaches in their understanding of the shot put landing position. The cues they were offering athletes can now be confirmed or refined given the results of this study. Future research should include analysis of variables that did not reach significance in the current study, such as S-H separation and PCOM. Additionally, knee and hip extension during the landing and completion phases might relate to thrown distance, and therefore should be included in future shot put kinematic research.

References

Ariel, G., Penny, A., Probe, J., Rudolf, B., Simonsen, E., Finch, A., & Judge, L. (2004). Biomechanical analysis of the shot-put event at the 2004 athens olympic games. *Ariel Dynamics*. http://www.arielnet.com/pages/show/adi-gba-01359/shotput-2004

Bajrić, O., Biberović, A., Saračević, Z., & Mikić, B. (2017). Influence of angular values of body segments on the distance of the throw out in (Z) axis. *Sports Science and Health, 7*(1),13-21. doi:10.7251/SSH1701013B

Bartoneitz, K. & Borgstrom, A. (1995). The throwing events at the World Championships in Athletics 1995, Goteborg - Technique of the world's best athletes Part 1: Shot put and hammer throw. *New Studies in Athletics*, *10*(4), 43-63.

Byun, K. O., Fujii, H., Murakami, M., Endo, T., Takesako, H., Gomi, K., & Tauchi, K. (2008). A biomechanical analysis of the men's shot put at the 2007 World Championships in Athletics. *New Studies in Athletics*, *23*(2). 53-62. http://www.richwoodstrack.com/rhs_team_area/throws/shot/tech_Biomechanical%20Analysis%20Worlds%202007.pdf

Göksu, Ö. & Kural, D. (2019). Evaluation of the effects of hip joint range of motion and trunk rotation on throwing biomechanics of shot putters: A pilot study. *Acta Medica Mediterranea*, *35*, 2823. 10.19193/0393-6384_2019_5_444.

Howard, R. M., Conway, R., & Harrison, A. J. (2017). Muscle activation sequencing of leg muscles during linear glide shot putting. *Sports Biomechanics*, *16*(4), 463-484. doi:10.1080/14763141.2016.1246601

Linthorne, N. P. (2001). Optimum release angle in the shot put. *Journal of Sports Sciences*, *19*(5), 359-372. DOI: 10.1080/02640410152006135

Manesh, K., Murali, M., & Dhinu, M. R. (2016). Kinematic analysis of shot release of intercollegiate athletes. *International Journal of Physical Education, Sports and Health. 3*(5), 131-134. http://www.kheljournal.com/archives/2016/vol3issue5/PartC/3-4-73-958.pdf

Saračević, Z, Atiković, A., Štuhec, S. S., & Čuk, I. (2018). How kinematics influences shot put results in track and field of international level athletes (a case study). *Journal of Physical Education and Sport, 1*(73), 512-516. DOI:10.7752/jpes.2018.s173

Schofield, M., Cronin, J. B., Macadam, P. & Hébert-Losier, K. (2022) Rotational shot put: a phase analysis of current kinematic knowledge, *Sports Biomechanics, 21*(3), 278-296, DOI: 10.1080/14763141.2019.1636130

Stander, R. (N.D.). Athletic onimbus- Shot put. http://www.sports-media.be/links/kogelstoten-engelstalig.pdf

Young, M. (2004). Critical factors for the shot put. *Track Coach, 166*, 5299-5304. http://www.coachkrall.com/Articles/Shot/shotcriticalfactors.pdf

Young, M. (2009). Development and application of an optimization model for elite level shot putting. *LSU Doctoral Dissertations, 25*. https://digitalcommons.lsu.edu/gradschool_dissertations/25