

THE Y-BALANCE TEST IN RUNNERS: RELATIONSHIPS BETWEEN PERFORMANCE
AND RUNNING MECHANICS, AND THE INFLUENCE OF FATIGUE

by

Charles Scott Wilson

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Exercise Physiology and Nutrition

MONTANA STATE UNIVERSITY
Bozeman, Montana

April 2020

©COPYRIGHT

by

Charles Scott Wilson

2020

All Rights Reserved

ACKNOWLEDGEMENTS

I would like to thank Sara Skammer and Sam Nelson for their great contributions to data collection and processing, and Allison Theobald for her consulting on statistical analyses. I would also like to thank my advisor, Dr. James Becker, for his guidance over the past several years. Finally, thank you to all of the graduate students in the Neuromuscular Biomechanics Laboratory. I have truly enjoyed learning and growing together.

TABLE OF CONTENTS

1. INTRODUCTION	1
REFERENCES CITED	4
2. LITERATURE REVIEW	8
Running, YBT Performance and Injury	8
Running Kinematics	9
Running Kinetics	11
Strength in Runners	13
Clinical Movement Screens.....	16
Star-Excursion Balance Test	18
Y-Balance Test	20
Validity of the Y-Balance Test.....	21
Y-Balance Test Performance and Strength	24
Y-Balance Test Performance and Injury	24
Running and Fatigue.....	26
Summary.....	28
REFERENCES CITED	29
3. A MULTIVARIATE ANALYSIS BETWEEN THE Y-BALANCE TEST AND INJURY-LINKED RUNNING MECHANICS	39
Introduction	42
Materials and Methods	45
Participants	45
Experimental Protocol	45
Data Analysis.....	47
Statistical Analysis	49
Results	50
Discussion.....	52
Conclusions	58
REFERENCES CITED	59

TABLE OF CONTENTS CONTINUED

4. THE RELATIONSHIP BETWEEN Y-BALANCE TEST PERFORMANCE AND RUNNING MECHANICS AT THE HIP FOLLOWING FATIGUE	65
Introduction	68
Materials and Methods	71
Participants	71
Experimental Protocol	71
Data Analysis.....	73
Statistical Analysis	75
Results	75
Discussion.....	77
Conclusions	82
REFERENCES CITED	84
5. DISCUSSION AND CONCLUSIONS	89
REFERENCES CITED	95
CUMULATIVE REFERENCES CITED.....	97

LIST OF TABLES

Table	Page
CHAPTER THREE	
1. Kinematic and Kinetic Running Gait Variables	48
2. Descriptive statistics for YBT and running mechanics variables.....	50
CHAPTER FOUR	
1. Descriptive statistics for running mechanics variables	76
2. Percent Change in Running Mechanics Between Pre and Post Fatigue Conditions	76
3. Descriptive Statistics for the Dominant Limb YBT	76

LIST OF FIGURES

Figure	Page
CHAPTER TWO	
1. Running Mechanics Previously Linked to Injury	9
2. Y-Balance Test Reach Directions	21
CHAPTER THREE	
1. Y-Balance Test Reach Directions	46
2. Linear Regressions Between Y-Balance Test Composite Score and Individual Running Gait Variables	51
3. CCA Between <i>Balance</i> and <i>Mechanics</i> Canonical Variables	52
CHAPTER FOUR	
1. Visual Depiction of the Y-Balance Test.....	73
2. Linear Regressions Between Individual Reach Directions and Running Gait Variables	77

CHAPTER ONE

INTRODUCTION

Running is one of the most widely engaged in forms of exercise throughout the world, and its applicability to almost all forms of sport makes running an essential component of athletic strength and conditioning programs.^{95,119} Yet, the value of running does not lie exclusively within training for athletic performance. Running is also an important tool in addressing the large-scale health concerns and associated financial costs with the increasing emergence of chronic diseases such as obesity.⁷ However, in order to reduce the prevalence of these issues people must not be prevented from running. One of the primary barriers restricting people from regular running is injury. For example, Van Gent et al. estimated that 19.4 – 79.3% of runners will experience injury during any given one-year period.¹¹⁸ Further, a more recent review of the running literature found that novice runners were more than twice as likely to develop injury per 1,000 hours of running compared to recreational runners.¹¹⁹ Many of the most common running injuries like patellofemoral pain,¹¹⁶ Iliotibial Band Syndrome⁸⁸ and Achilles Tendonitis⁴ have been linked to specific kinematic or kinetic patterns in running. Common running injuries have been retrospectively and prospectively linked to specific running mechanics. However, a gap still exists in the ability to predict said mechanics.

In order to reduce injury rates, it is important to identify individuals at risk prior to injury occurrence. Two-dimensional (2-D) analysis can be used to accurately identify biomechanical patterns associated with injury,⁷⁹ yet, it has several limitations. First, clinicians often have limited time with patients and may not have time to perform more

detailed diagnosing methods such as 2-D analysis. Second, 2-D analysis only allows for evaluation of a single plane at a time. 3-D kinematic and kinetic analysis is currently the gold standard for evaluating risk factors for running injuries in gait. However, the equipment and expertise required to utilize these tools are not readily accessible to lower-level sports teams or the general population, leaving a majority of those participating in exercise and sport at a disadvantage for injury prevention. While 3-D gait analysis may remain out of reach for those without the financial means or expertise to use it, a solution may lie within a variety of tests called clinical movement screens.

Clinical movement screens were developed to provide a measure or estimate for dynamic stability, strength and neuromuscular coordination, and are frequently used to evaluate injury risk.^{11,14,16,37,94} One of the most well-known movement screens is the Star-Excursion Balance Test (SEBT), a test often used in both athletic^{40,100} and clinical^{34,38} populations. However, a modification to the SEBT eventually gave rise to a new test, the Y-Balance Test (YBT). The YBT is similar to the SEBT but addressed a previous limitation in order to increase inter rater reliability.^{14,99} Since its inception, the YBT has also been used to evaluate lower extremity strength, balance and neuromuscular control in a variety of athletic^{25,46} and clinical⁵² populations. Additionally, the YBT has been proposed as a valid tool for injury prediction across a range of sports.^{37,100,107} To date, however, most research on the SEBT and YBT has focused on multisport populations^{107,130} or multidirectional sports such as basketball,¹⁰⁰ baseball¹¹ or soccer.³⁷

Hip strength has been identified as an essential component of YBT performance, with studies showing that increased strength of the muscle groups surrounding the hip is

related to greater reach distances.^{122,129} Likewise, retrospective^{31,91} and prospective^{71,104} studies have demonstrated a relationship between deficits in hip strength and several common running injuries. These connections suggest that YBT performance may be able to predict kinematic and kinetic patterns associated with hip weakness and, subsequently, greater risk of running injury. Investigation into whether YBT performance can reliably predict injury-linked running mechanics would clarify potential links between a well-known clinical movement screen and one of the world's most popular forms of exercise. Should the YBT be predictive of injury-linked running mechanics, it could provide a useful tool for runners, coaches and clinicians to identify and mitigate injury risks.

It is well-known that running long distances⁹⁵ or to volitional fatigue^{10,20,63,126} can lead to alterations in running mechanics. This implies that any associations between YBT performance and running mechanics will likely change along the course of a fatiguing run. Other clinical movement screens have previously been used to predict injury risk in distance runners.⁵³ Yet, no studies have evaluated the potential relationship between YBT performance and running mechanics. Additionally, no studies have examined whether YBT performance may predict changes in injury-related mechanics following a run to fatigue. While the YBT may be used to establish a baseline for return-to-sport readiness, it may also be able to provide an easy and inexpensive means to identify runners with particular mechanics that pose a greater risk for certain injuries. Thus, the purpose of this thesis is to examine the relationship between YBT performance and running mechanics previously linked to injury, and to determine if that relationship changes with fatigue.

REFERENCES CITED

4. Becker J, James S, Wayner R, Osternig L, Chou LS. Biomechanical Factors Associated With Achilles Tendinopathy and Medial Tibial Stress Syndrome in Runners. *Am J Sports Med.* 2017;45(11):2614-2621.
7. Bomberg E, Birch L, Endenburg N, et al. The Financial Costs, Behaviour and Psychology of Obesity: A One Health Analysis. *J Comp Pathol.* 2017;156(4):310-325.
10. Brown AM, Zifchock RA, Hillstrom HJ, Song J, Tucker CA. The effects of fatigue on lower extremity kinematics, kinetics and joint coupling in symptomatic female runners with iliotibial band syndrome. *Clin Biomech (Bristol, Avon).* 2016;39:84-90.
11. Butler RJ, Bullock G, Arnold T, Plisky P, Queen R. Competition-Level Differences on the Lower Quarter Y-Balance Test in Baseball Players. *J Athl Train.* 2016;51(12):997-1002.
14. Chimera NJ, Warren M. Use of clinical movement screening tests to predict injury in sport. *World J Orthop.* 2016;7(4):202-217.
16. Coughlan GF, Fullam K, Delahunt E, Gissane C, Caulfield BM. A comparison between performance on selected directions of the star excursion balance test and the Y balance test. *J Athl Train.* 2012;47(4):366-371.
20. Derrick TR, Dereu D, McLean SP. Impacts and kinematic adjustments during an exhaustive run. *Med Sci Sports Exerc.* 2001;34(6):998-1002.
25. Engquist KDS, Craig A.; Chimera, Nicole J.; Warren, Meghan. Performance Comparison of Student-Athletes and General College Students on the Functional Movement Screen and the Y Balance Test. *Journal of Strength and Conditioning Research.* 2015;28(8):2296-2303.
31. Fredericson M, Cookingham CL, Chaudhari AM, Dowell BC, Oestreicher N, Sahrmann SA. Hip Abductor Weakness in Distance Runners with Iliotibial Band Syndrome. *Clinical Journal of Sports Medicine.* 2000;10:169-175.

34. Gabriner ML, Houston MN, Kirby JL, Hoch MC. Contributing factors to star excursion balance test performance in individuals with chronic ankle instability. *Gait Posture*. 2015;41(4):912-916.
37. Gonell AC, Romero JAP, Soler LM. Relationship Between The Y Balance Test Scores and Soft Tissue Injury Incidence in a Soccer Team. *International Journal of Sports Physical Therapy*. 2015;10(7):955-966.
38. Gribble PA, Hertel J, Plisky P. Using the Star Excursion Balance Test to assess dynamic postural-control deficits and outcomes in lower extremity injury: a literature and systematic review. *J Athl Train*. 2012;47(3):339-357.
40. Gribble PA, Terada M, Beard MQ, et al. Prediction of Lateral Ankle Sprains in Football Players Based on Clinical Tests and Body Mass Index. *Am J Sports Med*. 2016;44(2):460-467.
46. Hartley EM, Hoch MC, Boling MC. Y-balance test performance and BMI are associated with ankle sprain injury in collegiate male athletes. *J Sci Med Sport*. 2018;21(7):676-680.
52. Hooper TL, James CR, Brismee JM, et al. Dynamic balance as measured by the Y-Balance Test is reduced in individuals with low back pain: A cross-sectional comparative study. *Phys Ther Sport*. 2016;22:29-34.
53. Hotta T, Nishiguchi S, Fukutani N, et al. Functional Movement Screen for Predicting Running Injuries in 18-to-24-Year-Old Competitive Male Runners. *Journal of Strength and Conditioning Research*. 2015;29(10):2808-2815.
63. Koblbauer IF, van Schooten KS, Verhagen EA, van Dieen JH. Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. *J Sci Med Sport*. 2014;17(4):419-424.
71. Leudke LE, Heiderscheit BC, Williams DSB, Rauh MJ. Association of Isometric Strength of Hip and Knee Muscles with Injury Risk in High School Cross Country Runners. *International Journal of Sports Physical Therapy*. 2015;10(6):868-876.
79. Maykut JNT-H, Jeffery A.; Paterno, Mark V.; DiCesare, Christopher A.; Ford, Kevin R. Concurrent Validity and Reliability of 2D Kinematic Analysis of Frontal

Plane Motion During Running. *International Journal of Sports Physical Therapy*. 2015;10(2):136-146.

88. Noehren B, Davis I, Hamill J. ASB clinical biomechanics award winner 2006 prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clin Biomech (Bristol, Avon)*. 2007;22(9):951-956.
91. Noehren B, Schmitz A, Hempel R, Westlake C, Black W. Assessment of strength, flexibility, and running mechanics in men with iliotibial band syndrome. *J Orthop Sports Phys Ther*. 2014;44(3):217-222.
94. Olmsted LCC, Christopher R.; Hertel, Jay; Shultz, Sandra J. Efficacy of the Star Excursion Balance Tests in Detecting Reach Deficits in Subjects With Chronic Ankle Instability. *Journal of Athletic Training*. 2002;37(4):501-506.
95. Paquette MR, Melcher DA. Impact of a Long Run on Injury-Related Biomechanics with Relation to Weekly Mileage in Trained Male Runners. *J Appl Biomech*. 2017;33(3):216-221.
99. Plisky PG, Paul P.; Butler, Robert J.; Kiesel, Kyle B.; Underwood, Frank B.; Elkins, Bryant. The Reliability of an Instrumented Device for Measuring Components of the Star Excursion Balance Test. *North American Journal of Sports Physical Therapy*. 2009;4(2):92-99.
100. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star Excursion Balance Test as a Predictor of Lower Extremity Injury in High School Basketball Players. *Journal of Orthopaedic and Sports Physical Therapy*. 2006;36(12):911-919.
104. Ramskov D, Barton C, Nielsen RO, Rasmussen S. High eccentric hip abduction strength reduces the risk of developing patellofemoral pain among novice runners initiating a self-structured running program: a 1-year observational study. *J Orthop Sports Phys Ther*. 2015;45(3):153-161.
107. Smith CA, Chimera NJ, Warren M. Association of y balance test reach asymmetry and injury in division I athletes. *Med Sci Sports Exerc*. 2015;47(1):136-141.

116. Thijs Y, De Clercq D, Roosen P, Witvrouw E. Gait-related intrinsic risk factors for patellofemoral pain in novice recreational runners. *Br J Sports Med.* 2008;42(6):466-471.
118. Van Gent RN, Siem D, Van Middelkoop M, Van Os AG, Bierma-Zeinstra SM, Koes BW. Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. *Br J Sports Med.* 2007;41(8):469-480; discussion 480.
119. Videbaek S, Bueno AM, Nielsen RO, Rasmussen S. Incidence of Running-Related Injuries Per 1000 h of running in Different Types of Runners: A Systematic Review and Meta-Analysis. *Sports Med.* 2015;45(7):1017-1026.
122. Walaszek RC, W.; Walaszek, K.; Burdacki, M.; Blaszczyk, J. Evaluation of the accuracy of the postural stability measurement with the Y-Balance Test based on levels of the biomechanical parameters. *Acta of Bioengineering and Biomechanics.* 2017;19(2):121-128.
126. Willson JD, Loss JR, Willy RW, Meardon SA. Sex differences in running mechanics and patellofemoral joint kinetics following an exhaustive run. *J Biomech.* 2015;48(15):4155-4159.
129. Wilson BR, Robertson KE, Burnham JM, Yonz MC, Ireland ML, Noehren B. The Relationship Between Hip Strength and the Y Balance Test. *J Sport Rehabil.* 2018;27(5):445-450.
130. Wright AA, Dischiavi SL, Smoliga JM, Taylor JB, Hegedus EJ. Association of Lower Quarter Y-Balance Test with lower extremity injury in NCAA Division 1 athletes: an independent validation study. *Physiotherapy.* 2017;103(2):231-236.

CHAPTER TWO

LITERATURE REVIEW

Running, YBT performance and Injury

Proponents claim that YBT performance is sensitive to deficits in strength,¹²⁹ dynamic joint stability⁹⁶ and neuromuscular control,^{5,11,25} but the primary claim of the YBT is its ability to predict risk of subsequent injury.³⁷ To our knowledge, no studies have examined the ability of the YBT to predict injury in runners. Running injuries are primarily overuse in nature, and result from the cyclic application of loads combined with specific kinematic and kinetic patterns.^{82,125} Many studies have established relationships between common running injuries and specific running mechanics, though relatively few of these relationships were established through prospective studies. Studies have also demonstrated that running mechanics linked to injury may also be related to deficits in strength or neuromuscular control of the lower extremities. Thus, YBT performance may be able to predict certain injury-linked running mechanics given the similarities between the two tasks. This review will highlight running mechanics that have been linked to common running injuries while relying heavily on prospective studies. An examination of commonly used clinical movement screens including a detailed background on the YBT will follow.

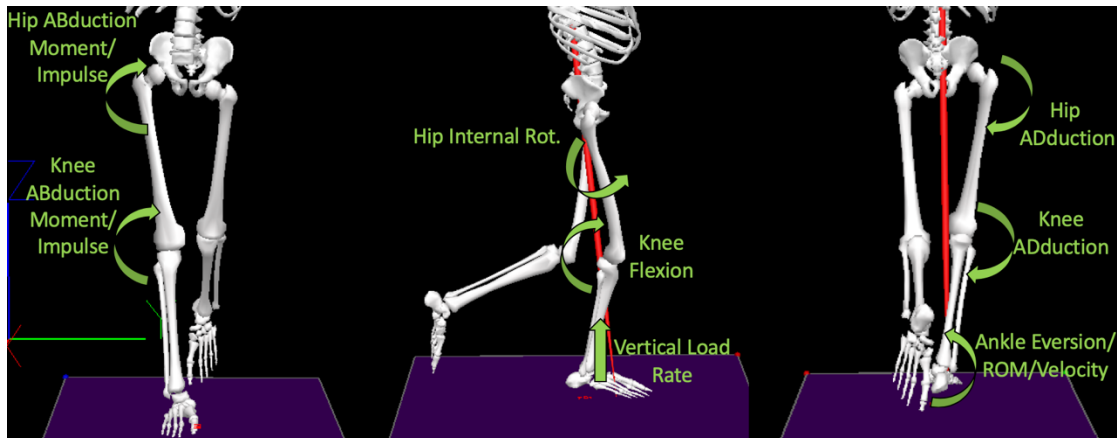


Figure 1. Running variables that have been previously associated with common running injuries (see Study 1 for citations). Kinetic variables reflect internal joint moments and impulses. Image views are front, right side and back (left to right).

Running Kinematics

The hip is one of the three major joints in the lower extremity and has tremendous influence over balance, especially during dynamic tasks such as running. Altered mechanics at the hip are often linked to running-related injuries, with excessive hip adduction and internal rotation cited as some of the most common causes of injury.^{90,101} A prospective study by Noehren et al. examined potential links between running kinematics and one of the most common running-related injuries, Iliotibial-Band Syndrome (ITBS).⁸⁸ Noehren et al. found that runners who developed ITBS over the two-year period demonstrated greater hip adduction during testing. ITBS has been defined as pain on the lateral aspect of the knee, and is hypothesized to result from friction or compression of the IT-Band on the lateral femoral epicondyle following heel strike.^{3,88} Noehren et al.'s findings support the theory that excessive adduction of the hip increases IT-Band strain on the lateral femoral epicondyle⁴⁴ and, with repetitive application of loads, can eventually lead to ITBS.

A second study by Noehren et al. examined 400 experienced female runners averaging 20 miles of running per week. It was hypothesized that runners who displayed greater hip adduction, internal rotation and rear foot eversion would develop patellofemoral pain (PFP).⁸⁹ However, the study found that those who went on to develop PFP only showed higher peak hip adduction during stance phase. Runners with PFP tend to have increased contact stresses on the lateral aspect of the patella,²⁷ and excessive hip adduction has been shown to increase this stress.⁸⁹ Ferber et al. also found that runners previously diagnosed with ITBS displayed greater hip adduction.²⁸ Additionally, transverse plane kinematics have been implicated in running injury. A retrospective study by Souza et al. found that runners with PFP displayed greater hip internal rotation compared to healthy controls.¹⁰⁹ Though the Ferber et al. and Souza et al.'s studies were retrospective, these results combined with Noehren et al.'s findings provide strong evidence suggesting that abnormal hip kinematics may create a predisposition to running injuries.

There are fewer prospective studies examining the role of knee kinematics in the development of running injury. However, the knee is by far the most commonly injured site for runners,^{82,113} and abnormal knee mechanics have frequently been cited as contributors to running injury.²⁸ The same prospective study by Noehren et al. which linked hip adduction to ITBS also found that runners who developed ITBS displayed greater knee internal rotation.⁸⁸ Further, the retrospective study by Ferber et al. also compared knee kinematics between runners with and without a history of ITBS, and Ferber et al. also found that runners diagnosed with ITBS displayed greater knee internal

rotation.²⁸ Baker et al. also found further implications for knee kinematics in the development of running injury.³ In Baker's study runners with ITBS demonstrated increased knee adduction compared to runners without a history of ITBS.

Kinematics at the ankle have also been implicated in the origin of various running injuries. A study by Dudley et al. prospectively compared the running kinematics of cross-country runners throughout their season.²² Of the 31 participants, 12 were injured, and Dudley et al. found that the injured runners demonstrated greater peak ankle eversion velocity compared to non-injured runners. However, this is in direct contradiction to a previous study by Kuhman et al. who found that un-injured runners had greater eversion range of motion and eversion velocity, but reduced peak eversion angle.⁶⁵ Though these studies appear to contradict one another, both sets of study participants experienced different injuries, which may explain the variations in kinematic differences between injured and uninjured runners. A retrospective study by Becker et al. found greater eversion duration, but no differences in eversion velocity between runners currently symptomatic with either Achilles Tendinopathy or Medial Tibial Stress Syndrome and healthy controls.⁴ More prospective studies should be conducted on the relationships between ankle kinematics and running injury, but it appears that kinematics at the hip and knee play a greater role in the development of running related injuries such as ITBS and PFP compared to the ankle.

Running Kinetics and Injury

Segment orientation and joint angles are intrinsically related to the kinetic forces experienced by the joints that contribute to injury. The involved tissues are subject to

these repetitive stresses over time and can lead to various types of running injuries. A prospective study by Eskofier et al. observed that runners with higher peak internal hip abductor moments developed PFP in the six months following the study.²⁶ Another prospective study by Stefanyshyn et al. examined frontal plane knee kinematics in runners with PFP compared to asymptomatic controls.¹¹⁰ The study was unique in that it was divided into prospective and retrospective components. According to the results, runners who either developed or possessed PFP had greater internal knee abduction impulses. Stefanyshyn et al. proposed that greater hip adduction causes a larger internal abduction moment, which places more stress on the lateral aspect of the patella by overpowering its medial stabilizers, leading to PFP. These results were further confirmed by Dudley et al. who conducted a prospective study on collegiate cross-country runners. Dudley et al. found that runners who displayed larger peak external knee adduction moments were more likely to become injured in the subsequent season.²² However, the runners in this study sustained a variety of injuries. Thus, no direct relationship can be established between greater external knee adduction moments and the development of PFP.

There is some evidence that increased loading rates and braking forces may also contribute to the development of running injury. A prospective study by Thijs et al. found that recreational runners who went on to develop PFP displayed greater rates of force production under the lateral heel during heel strike, as well as higher peak vertical propulsive forces under the 2nd – 3rd metatarsals.¹¹⁶ In contrast, Davis et al. conducted a study where they found no differences in impact-related variables between injured and

un-injured runners over the two-year study period.¹⁸ Participants of the Davis et al. study self-reported injuries via surveys and not all injuries were medically diagnosed. Though, of the injuries that were medically diagnosed all impact-related variables were higher. Napier et al. also conducted a prospective study on 65 recreational runners and found that those who became injured demonstrated higher peak braking forces.⁸⁶ However, there were no differences in loading rates between injured and un-injured subjects. Finally, Milner et al. observed that female runners with a history of tibial stress fractures displayed greater vertical loading rates compared to healthy controls.⁸⁴ Though there is mixed evidence for the influence of kinetic factors on injury risk, it appears that frontal plane kinetics are most implicated in the development of running injury.

Strength in Runners

The ability to resist cyclic loads and maintain the forward momentum during running requires strength, and deficits in strength have long been theorized to contribute to the development of running injuries. Literature examining strength in runners has primarily focused on the musculature surrounding the hip and thigh. A variety of risk factors have been proposed in the development of running injury including weakness and/or tightness of the quadriceps⁹⁷ and weakness of the hip musculature.^{58,61} For example, a cross-sectional study by Noehren et al. found that male runners with ITBS had weaker hip external rotators compared to healthy controls.⁹¹ However, there have been conflicting results between studies that have examined relationships between strength of the musculature surrounding the hip and running injury. Piva et al. found no difference in external rotation or abduction strength between runners with and without PFP.⁹⁷

In novice runners, Thjis et al. conducted a prospective study where 77 female subjects without a history of PFP participated in a 10-week “start to run” program.¹¹⁷ Isometric strength of the hip muscle groups were taken prior to the program and injured runners were diagnosed by an orthopedic surgeon. 16 of the runners were diagnosed with PFP, but the study did not find any differences in strength between the runners who did or did not develop PFP. A later study by Ramskov et al. followed 629 novice runners for a year and found that runners with weaker hip adductors had an increased likelihood of developing patellofemoral pain.¹⁰⁴ The Ramskov et al. study also utilized eccentric contractions, which are more similar to the types of muscular contractions used while running. The differences between the results of Thjis et al. and Ramskov et al. may be explained by the type of muscle contraction used for strength testing. It is also worth noting that both the Ramskov et al. and Thjis et al. studies utilized novice runners. Thus, these results may not apply to experienced distance runners.

There is some evidence that strength training may be linked to the alleviation of pain from common running injuries. Fredericson et al. placed 24 distance runners with ITBS on a six-week training program targeting the Gluteus Medius.³¹ After the program, 22 of the 24 runners experienced complete resolution of their pain and were able to return to running. It is unknown, however, whether improvements in strength led to decreased hip adduction during running as kinematics were not evaluated. Earl et al. later conducted a similar study where 19 women with PFP completed an eight-week program designed to improve strength and neuromuscular control of the hip.²³ Findings from Earl et al.’s study revealed improvements in hip abduction and external rotation strength, as well as pain.

Runners also experienced reduced internal knee abduction moments following the rehabilitation program. However, Earl et al. reported no differences in hip abduction range of motion. It is interesting that improvements in pain were only related to increased muscle strength, and not improvements in hip abduction. One explanation may be that while abduction range of motion remained the same, peak abduction may have been reduced. It is also possible that the strengthening program caused neurological adaptations that increased the ability to withstand pain. While there is still much research to be done in this area, both Fredericson and Earl's studies provide powerful evidence for the role of strength in mitigating pain from running-related injuries.

Strength training has been shown to improve gait in some clinical populations¹⁷ but may not change gait in runners.¹²⁷ Willy et al. performed a study where 20 healthy female athletes with excessive hip adduction (defined as at least 20°) underwent a hip-strengthening program.¹²⁷ After a six-week training program hip adduction, internal rotation and contralateral pelvic drop during running all remained the same. The interesting result, however, was that these variables all decreased during single-leg squat performance. The Single-Leg Squat uses many of the same muscles and coordination patterns as running. Further, the Single-Leg Squat also uses eccentric contractions for stabilization similar to running. Thus, it is uncertain whether strength training alters kinematics, increases the tissues' ability to withstand stress or incites some other neurological response that improves pain.

Clinical Movement Screens

While balance and strength have long been noted as primary determinants of athletic performance, evaluations of clinical movement screens such as the YBT only began appearing in the literature roughly 20 years ago.^{24,62} Clinical movement screens are tests designed to provide a measure for balance, strength and neuromuscular control, and have been suggested to predict injury risk across a variety of sports.^{37,40,74} However, few studies on clinical movement screens have specifically studied distance runners. This section will briefly review several well-known clinical movement screens including the Single-Leg Step Down (SLSD), Single-Leg Squat (SLS) and Functional Movement Screen (FMS), while a detailed review of both the SEBT and YBT will follow.

One of the most common movement screens used to evaluate strength, balance and neuromuscular coordination in runners is the SLSD, also known as the Step-Down Test. The SLSD is primarily used to evaluate strength and dynamic coordination of the muscles surrounding the hip.⁷⁷ During this test the patient is asked to maintain a single-leg stance on a 20 cm box – or a box approximately 10% of the patient's height – and gently touch the non-stance heel to the ground. During the test the clinician, coach or investigator visually assesses performance by looking for specific criteria that may indicate dysfunction including, but not limited to: arm or trunk movement to recover or maintain balance, imbalances in pelvic rotation or elevation, medial knee collapse and inability to maintain unilateral stance.⁷⁷ Any of the designated movements are said to be indicative of dysfunctions in strength and neuromuscular control of the lower extremity.⁵¹

A similar movement screen called the SLS is also used to test the ability to progressively load the lower limbs.⁷⁷ This loading analyzes the ability of the quadriceps to eccentrically bear the load applied during running, as well as the ability of the hip muscles to stabilize the pelvis and thigh. Inability to perform these tasks may indicate muscular weakness and a predisposition to injury-related running mechanics.¹²⁸ The clinical significance of this test is not limited to the hip but also extends to the ankle, and is used to assess dorsiflexion range of motion. Limited dorsiflexion may cause compensatory increased pronation, potentially placing runners at greater risk of injuries such as medial-tibial stress syndrome.⁷⁷

Another clinical movement screen that has gained popularity in recent years is the FMS. The FMS is used to evaluate stability and range of motion of the major joints.¹⁴ However, the test is unique in that it is a full-body screen, requiring the participant to perform movements using all of the major joints including the hip, knee, ankle and shoulder. Each movement is given a score based on the participant's performance which are summed to yield a composite score. The FMS is one of the few movement screens that have been evaluated in runners. Hotta et al. conducted a prospective study on 18 – 24 year-old competitive runners and found that FMS performance was significantly associated with injury in the following season.⁵³ However, there has been criticism in recent years regarding the ability of movement screens – specifically the FMS – to predict injury risk.⁸⁵ One of the main criticisms is the inconsistent definition of injury utilized in movement screen research, which may prohibit researchers from determining the true validity of these tests in predicting injury risk. A second criticism attacks the

main metric of interest, the composite score. Historically, the composite score has been heavily relied upon as a predictor of injury risk. However, recently, the individual components of these tests have been suggested to be more useful than the composite scores themselves.^{40,107} This claim is supported Hotta et al.'s findings that the Deep Squat and Active Straight Leg Raise components of the FMS were associated with subsequent injury, but not the FMS composite score.⁵³

Clinical movement screens have been widely used as a measure of strength, muscular coordination and dynamic balance of the lower extremity. These tests have also been frequently suggested to be reliable predictors of injury risk. However, there has been conflicting evidence regarding the relationship between movement screen performance and injury risk. The umbrella of clinical movement screens includes a wide variety of tests that cannot be addressed within the limits of this manuscript. Thus, the remainder of this paper will focus on the SEBT and its derivative, the YBT.

Star-Excursion Balance Test

It is unknown when the SEBT was first created, but Kinzey et al. conducted the first known study specifically investigating the SEBT in 1998.⁶² The study examined the SEBT's reliability by measuring the ability of healthy subjects to demonstrate consistency in performance. Kinzey's pre/post-test design found that the SEBT was only moderately reliable, even after several practice sessions. Kinzey concluded that the unreliability of the SEBT was reflected as "a change in score due to some unmeasurable circumstance, a random movement pattern, or any other possible influence, including mental state," leading to the conclusion that the SEBT may not be a useful clinical

measure.⁶² However, Kinzey et al.'s protocol differed significantly from the current SEBT in several ways. First, Kinzey used four of the reach directions (resembling an "X" pattern) instead of the traditional eight-direction star-pattern.¹⁴ Second, Kinzey did not include the anterior reach direction, which is often cited as the most important reach direction in relation to injury prediction.^{98,107} Third, subjects in Kinzey et al.'s study were not allowed to touch down with the reach foot at maximal reach. Lastly, the subjects performed the test with shoes on, while it is commonly accepted that movement screens should be performed barefoot to accurately measure dynamic balance and muscular coordination. However, there is some question as to whether these tests should be performed in sport-specific footwear. Nonetheless, the current version of the SEBT has evolved significantly since Kinzey et al.'s study, hence, their findings should not be applied to the modern version.

The original SEBT protocol utilized an eight-arm star pattern.¹⁴ To perform the test the participant is asked to stand in the center of the star and reach as far as they can in each of the eight directions while maintaining single-limb balance. Most studies have allowed the subject to return to bi-lateral stance between each reach,^{29,33,62,93} while others do not specify this parameter. Each reach distance is then used to calculate a composite score, with a higher score proposed to indicate greater stability and neuromuscular control.¹⁴ Greater dynamic stability and strength is suggested to be associated with a reduced risk of injury. However, the eight direction SEBT was found to be redundant when Hertel et al. compared performance between individuals with chronic ankle instability and healthy controls. Hertel et al. only finding differences in SEBT

performance in the anterior-medial, medial and posterior-medial directions.⁴⁷ These findings catalyzed the development of the “modified” SEBT by trimming eight directions down to three: anterior (A), posterior-medial (PM) and posterior-lateral (PL). The validity of the three-direction test was further supported by Hubbard et al. who observed that individuals with chronic ankle instability displayed greater deficits in between-limb performance in the ANT and PM directions compared to healthy controls.⁵⁶ Additionally, Hale et al. found that participants with CAI that completed a rehabilitation protocol only improved in the PL, PM and lateral directions of the 8-direction SEBT.⁴²

Studies examining the SEBT have primarily focused on clinical evaluations of those with and without a history of ankle injury.^{19,41,47,49,57} Several studies have also established prospective links between SEBT performance and injury risk in athletic populations.^{40,100,112} Despite this the SEBT has experienced various criticisms, mainly directed towards the validity of composite scores in predicting injury risk. However, the SEBT protocol requires the stance foot to maintain full contact with the ground and does not allow for heel lift. The ability of the rater to reliably distinguish heel lift was called into question,¹⁴ and was later addressed by the proposal of a new movement screen called the Y-Balance Test (YBT).

Y-Balance Test

The YBT was modified from the SEBT to allow for stance foot heel lift,¹⁴ pioneering the development of a proprietary YBT device (Functional Movement Systems, Chatham, VA). The YBT device is constructed of a platform with three polyvinylchloride pipes, and reaches are performed by pushing a block along each of the

pipes as far as possible while maintaining single-limb stance. During the test participants must keep their hands on their hips and cannot use the reach foot for support. High inter and intra-rater reliability have been reported for the YBT,⁹⁹ with some reporting even higher reliability compared to the SEBT.³⁹

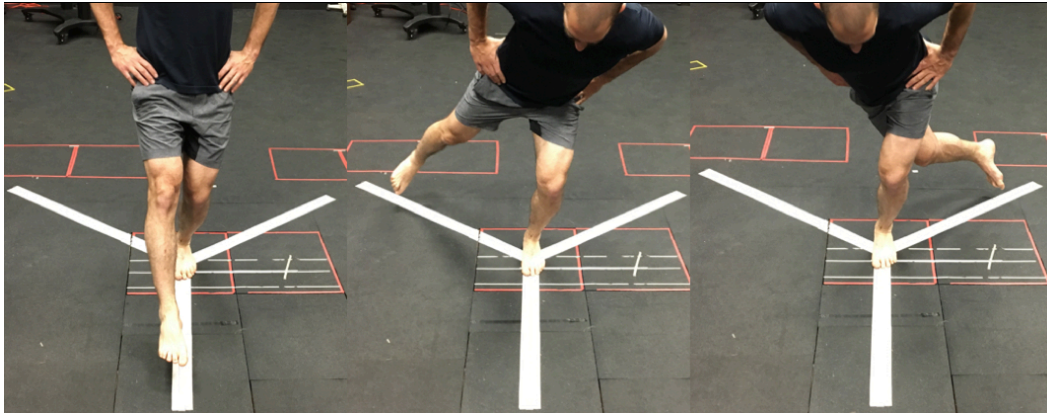


Figure 1. Y-balance Test reaches performed in the anterior, posterior-medial and posterior-lateral directions (left to right)

Validity of the Y-Balance Test

While the YBT device is considered a reliable substitute for the SEBT, there are several factors that can result in slight differences in performance. It has been shown that allowing for heel lift contributes to the kinematic changes that can result in slight differences in reach performance; and these changes are suggested to stem from differences in neuromuscular demands.³³ Another factor, however, that may contribute to differences in performance is focus of attention. It has been shown that foci of attention can significantly impact performance and may lead to differences in task outcomes.⁷⁵ The YBT device relies on an external focus of attention – instructing the subject push a block as far as possible – whereas the SEBT relies on an internal focus of attention, instructing the participant to reach as far as possible. Coughlan et al. found that subjects reached

farther in the ANT direction of the SEBT compared to the YBT, proposing that differences in focus of attention and neural feedback contributed to differences in performance.¹⁶ Fullam et al. confirmed the results of Coughlan et al., finding that subjects reached farther and had increased hip flexion during the ANT reach of the SEBT compared to the YBT.³³ Though it appears that focus of attention can result in slight variations in performance between the two tests, one would expect differences in all three reach directions if focus of attention were a primary influencer. Despite slight differences in performance it is generally accepted that the YBT can be performed with or without the YBT device, so long as the main criteria are fulfilled.¹²¹

The YBT has previously been used in a variety of settings to identify deficits in neuromuscular coordination, strength and dynamic joint stability. Research on the SEBT has historically focused primarily on clinical populations such as those with CAI,^{21,34,49,56} and several studies have also evaluated the YBT in clinical settings. Payne et al. conducted a study involving male soccer athletes with and without CAI and found that the healthy group reached farther in the ANT direction.⁹⁶ Subjects also currently symptomatic with or possessing a history of low back pain showed reduced PM and PL reach performance compared to healthy controls.⁵² These results would be expected because the posterior reach directions require much greater amounts of hip flexion and forward trunk lean, increasing the torque on the lumbar spine.⁶⁰ While some research has studied the YBT in clinical populations, a majority of the YBT literature focuses on the ability to predict injury in athletic populations.

A major claim of YBT proponents is that the test is a measure of neuromuscular coordination. Benis et al. tested this claim by conducting a study where female basketball players underwent an 8-week neuromuscular training intervention.⁵ YBT reach in the PM/PL directions and CS all improved following the intervention, providing support for the YBT's validity as a measure of neuromuscular control. A similar study by Vitale et al. also found that an eight-week neuromuscular training program improved YBT performance in elite junior skiers.¹²⁰ Several studies have also compared YBT performance between various levels of athletes, or between athletes and the general population. Butler et al. found differences in YBT performance between different levels of soccer players, providing evidence that greater levels of strength and coordination can lead to increases in YBT performance.¹² Between high school, collegiate and professional soccer players, the collegiate and professional groups demonstrated greater normalized PM/PL reaches and CS. Butler et al. conducted a similar study on baseball players, again, finding a trend towards increased YBT performance in higher-level athletes.¹¹ Engquist et al. also found that collegiate athletes performed better than the general student population on the YBT.²⁵ Engquist et al. observed that only female athletes performed better compared to female non-athletes, these results still lend credit to the YBT's validity in measuring strength and neuromuscular coordination.

Though no studies have evaluated muscle activation patterns of the YBT, several have investigated these differences in the SEBT. Norris et al. found that the activation levels of Gluteus Maximus and Vastus Medialis were similar in all three directions of the SEBT, but Gluteus Medius activation was lower in the PM direction.⁹² Earl et al. found

that Biceps Femoris activity was greatest in the posterior reach directions of the SEBT.²⁴ These results confirm that different reach directions of the YBT require various muscle coordination patterns. Thus, specific reach directions may be used to isolate a particular muscle group during screening or rehabilitation.

Y-Balance Test Performance and Strength: Proponents also claim that the YBT is a valid – yet, indirect – measure of lower-extremity strength. McCann et. al. previously supported this claim by demonstrating that hip strength is essential to SEBT performance.⁸⁰ Lawrence et al. also found that YBT performance was positively correlated with vertical jump height, concluding that it is a valid measure of strength and muscular coordination.⁶⁷ More recently, Wilson et al. demonstrated a positive correlation between hip abduction, extension and external rotation strength and YBT performance.¹²⁹ It has also been shown that adolescent soccer players with symptoms of hip or groin injury demonstrated reduced PL and PM reach compared to healthy controls.⁷⁴ However, the YBT may only be a reliable indicator of strength of the muscle groups surrounding the hip and thigh, as Hall et al. saw no increases in performance after subjects with completed rehabilitation protocols designed to improve strength of the musculature surrounding the ankle.⁴³

Y-Balance Test Performance and Injury: Because the YBT is considered a valid measure of strength, dynamic joint stability and neuromuscular coordination, the majority of studies have assessed the YBT's ability to predict injury in athletics. One of the most common sport populations the YBT has studied in is soccer. In prospective a study by Gonell et al. 74 professional male soccer players completed a preseason YBT

screening.³⁷ Gonell et al. reported that those with a CS below the population average were two times more likely to experience injury. Players with a PM asymmetry greater than 4 cm were also four times more likely to experience non-contact injury. However, Gonell et al. did not allow for stance foot heel lift during the YBT. Less common sport populations such as netball have also been studied. Lee et al. compared YBT scores with knee valgus moments during unplanned sidestepping, a common scenario for ACL injury.⁶⁹ PL reach and CS were negatively correlated with peak knee valgus moments and, thus, may indicate a reduced risk of ACL injury according to Lee et al. A majority of studies on the YBT in athletics have also examined multisport populations. Chimera et al. found that injury history did not affect YBT performance in Division-I athletes.¹³ Hartley et al. also performed a prospective study on Division-I athletes and found that the combination of high Body-Mass Index and low ANT reach were associated with a greater risk for ankle injury.⁴⁶

The YBT is most often used to predict injury in athletic populations but is also used in rehabilitation to gauge return to sport readiness.¹²¹ A study by Garrison et al. divided 43 participants that were currently rehabilitating from ACL reconstruction into two groups: traditional rehabilitation and rehabilitation plus a hip-specific strengthening program.³⁵ After 12 weeks, the group that participated in the hip-strengthening protocol had smaller ANT reach asymmetries as measured from the YBT, and according to Garrison et al., improved dynamic balance. However, it is difficult to determine whether the improvement in dynamic balance was due to strengthening or neural adaptations as Garrison et al. did not measure strength. Conversely, Mayer et al. conducted a study

comparing YBT performance between patients released or not released to return to sport following ACL reconstruction surgery and did not find differences in YBT or FMS performance.⁷⁸ Mayer et al. argues that these results indicate movement screens may not be able to detect the neuromuscular imbalances that may predispose athletes to re-injury.

Additional studies have found the YBT to be ineffective in establishing a link between performance and subsequent injury. A prospective study by Lai et al followed 294 Division-I athletes throughout the course of their respective seasons and found no correlation between side-specific reach asymmetry and injury for all three reach directions.⁶⁶ However, Lai et al. did find a very weak correlation between CS and number of injuries to the corresponding limb. It is generally accepted that a reach asymmetry of greater than 4 cm is associated with greater risk of injury in either the SEBT¹⁰⁰ or YBT.^{37,107} However, Lai et al. only found that an ANT reach asymmetry greater than 2 cm and PL reach asymmetry greater than 3 cm were associated with a lower number of injuries. A similar study was conducted by Wright et al. with 189 Division-I athletes.¹³⁰ The study also found no relationship between YBT performance and subsequent injury. Further research is needed to confirm the YBT's validity in detecting neuromuscular deficits or predicting injury risk. But a new perspective may soon provide the insight needed to clarify the YBT's usefulness in the clinic and sport.

Running and Fatigue

A number of studies have demonstrated that kinematic and kinetic changes can occur along the course of a fatiguing run. Paquette et al. conducted a study to investigate the effects of a long treadmill run on running mechanics previously linked to injury.⁹⁵

Out of the 12 kinematic and kinetic variables analyzed only vertical loading rate was different, being slightly higher after the fatiguing run. A study by Giandolini et al. examined distance runners before and after a 110 km race.³⁶ Giandolini et al. noted that runners altered foot strike along the course of the run and that alterations were correlated with plantar-flexor fatigue. This suggests that muscular fatigue leads to kinematic changes which could alter kinetics and, subsequently, injury risk. Radzak et al. also found that a fatiguing run led to increased biomechanical asymmetries between limbs; specifically in knee internal rotation, knee stiffness, vertical loading rate and adduction free moment.¹⁰³ However, the fatigue protocol was a high-intensity run with a mean time to exhaustion of roughly six minutes. These findings may not be applicable to fatigue experienced by longer, lower intensity runs.

While several studies have found differences in kinematics and kinetics between fresh and fatigued states, others provide evidence suggesting that fatigue may not influence running mechanics. Brown et al. found no differences in running kinematics or kinetics between pre and post a fatiguing run; also noting no differences between dominant and non-dominant limbs.⁹ A study by Abt et al. also found no differences in knee flexion, pronation or shock absorption after a fatiguing run.¹ Mean time to exhaustion for these studies were 24 minutes and 17 minutes, respectively. Thus, results from these studies may be more applicable to the distance running population. Some studies have also contradicted the theory that increased hip adduction is associated with running injury.^{88,89} A later study by Brown et al. examining female distance runners found that those with ITBS had reduced hip adduction, abductor moments and external

rotator moments following fatigue but noted no other changes in kinematics, kinetics or joint coupling in either group.¹⁰ Brown et al., however, point out that decreasing hip adduction could be a method of dealing with the pain from ITBS, reducing strain on the IT-Band. Yet, this suggests that runners with ITBS may not have hip abductor weakness, indicating that weakness in these muscles may not play a role in fatigue-induced alterations in kinematics. This also contradicts previous findings that strengthening the hip abductors can reduce pain in injured runners.^{23,31}

Summary

Injuries in runners are primarily overuse in nature and occur due to repetitive stress on the involved tissues. Relationships between strength and neuromuscular control – primarily of the hip and thigh – and YBT performance have been well established. Deficits in strength, dynamic joint stability and neuromuscular control of the muscles surrounding the hip and thigh may compound over time and potentially accelerate injury in runners. Thus, a test that can reliably detect the existence of such deficits could be useful in the prevention of running injuries. The YBT has been studied in a variety of athletic populations. Yet, research has not specifically evaluated the YBT in relation to one of the world's most popular forms of exercise, distance runners. The following manuscripts will evaluate the relationship between YBT performance and running mechanics linked to injury. Further, the effect of fatigue on these relationships will be examined.

REFERENCES CITED

1. Abt JPS, Tomithy C.; Chu, Yungchien; Lovalekar, Mita; Burdett, Ray G.; Lephart, Scott M. Running kinematics and shock absorption do not change after brief exhaustivte running. *Journal of Strength and Conditioning Research*. 2011;26(6):1479-1485.
3. Baker RL, Souza RB, Rauh MJ, Fredericson M, Rosenthal MD. Differences in Knee and Hip Adduction and Hip Muscle Activation in Runners With and Without Iliotibial Band Syndrome. *PM R*. 2018;10(10):1032-1039.
4. Becker J, James S, Wayner R, Osternig L, Chou LS. Biomechanical Factors Associated With Achilles Tendinopathy and Medial Tibial Stress Syndrome in Runners. *Am J Sports Med*. 2017;45(11):2614-2621.
5. Benis R, Bonato M, La Torre A. Elite Female Basketball Players' Body-Weight Neuromuscular Training and Performance on the Y-Balance Test. *J Athl Train*. 2016;51(9):688-695.
9. Brown AM, Zifchock RA, Hillstrom HJ. The effects of limb dominance and fatigue on running biomechanics. *Gait Posture*. 2014;39(3):915-919.
10. Brown AM, Zifchock RA, Hillstrom HJ, Song J, Tucker CA. The effects of fatigue on lower extremity kinematics, kinetics and joint coupling in symptomatic female runners with iliotibial band syndrome. *Clin Biomech (Bristol, Avon)*. 2016;39:84-90.
11. Butler RJ, Bullock G, Arnold T, Plisky P, Queen R. Competition-Level Differences on the Lower Quarter Y-Balance Test in Baseball Players. *J Athl Train*. 2016;51(12):997-1002.
12. Butler RJ, Southers C, Gorman PP, Kiesel KB, Plisky PJ. Differences in soccer players' dynamic balance across levels of competition. *J Athl Train*. 2012;47(6):616-620.
13. Chimera NJ, Smith CA, Warren M. Injury history, sex, and performance on the functional movement screen and Y balance test. *J Athl Train*. 2015;50(5):475-485.

14. Chimera NJ, Warren M. Use of clinical movement screening tests to predict injury in sport. *World J Orthop.* 2016;7(4):202-217.
16. Coughlan GF, Fullam K, Delahunt E, Gissane C, Caulfield BM. A comparison between performance on selected directions of the star excursion balance test and the Y balance test. *J Athl Train.* 2012;47(4):366-371.
17. Damiano DLA, Allison S.; Steele, Katherine M.; Delp, Scott L. Can strength training predictably improve gait kinematics? A pilot study on the effects of hip and knee extensor strengthening on lower-extremity alignment in cerebral palsy. *Phys Ther.* 2010;90(2):269-279.
18. Davis IS, Bowser BJ, Mullineaux DR. Greater vertical impact loading in female runners with medically diagnosed injuries: a prospective investigation. *Br J Sports Med.* 2016;50(14):887-892.
19. de la Motte S, Arnold BL, Ross SE. Trunk-rotation differences at maximal reach of the star excursion balance test in participants with chronic ankle instability. *J Athl Train.* 2015;50(4):358-365.
21. Doherty C, Bleakley C, Hertel J, Caulfield B, Ryan J, Delahunt E. Dynamic balance deficits in individuals with chronic ankle instability compared to ankle sprain copers 1 year after a first-time lateral ankle sprain injury. *Knee Surg Sports Traumatol Arthrosc.* 2016;24(4):1086-1095.
22. Dudley RI, Pamukoff DN, Lynn SK, Kersey RD, Noffal GJ. A prospective comparison of lower extremity kinematics and kinetics between injured and non-injured collegiate cross country runners. *Hum Mov Sci.* 2017;52:197-202.
23. Earl JE, Hoch AZ. A proximal strengthening program improves pain, function, and biomechanics in women with patellofemoral pain syndrome. *Am J Sports Med.* 2011;39(1):154-163.
24. Earl JH, Jay. Lower-Extremity Muscle Activation During the Star Excursion Balance Tests. *J Sport Rehabil.* 2001;10:93-104.
25. Engquist KDS, Craig A.; Chimera, Nicole J.; Warren, Meghan. Performance Comparison of Student-Athletes and General College Students on the Functional

Movement Screen and the Y Balance Test. *Journal of Strength and Conditioning Research*. 2015;28(8):2296-2303.

26. Eskofier BM, Kraus M, Worobets JT, Stefanyshyn DJ, Nigg BM. Pattern classification of kinematic and kinetic running data to distinguish gender, shod/barefoot and injury groups with feature ranking. *Comput Methods Biomech Biomed Engin*. 2012;15(5):467-474.
27. Farrokhi S, Keyak JH, Powers CM. Individuals with patellofemoral pain exhibit greater patellofemoral joint stress: a finite element analysis study. *Osteoarthritis Cartilage*. 2011;19(3):287-294.
28. Ferber R, Noehren B, Hamill J, Davis IS. Competitive female runners with a history of iliotibial band syndrome demonstrate atypical hip and knee kinematics. *J Orthop Sports Phys Ther*. 2010;40(2):52-58.
29. Filipa A, Byrnes R, Paterno MV, Myer GD, Hewett TE. Neuromuscular training improves performance on the star excursion balance test in young female athletes. *J Orthop Sports Phys Ther*. 2010;40(9):551-558.
31. Fredericson M, Cookingham CL, Chaudhari AM, Dowell BC, Oestreicher N, Sahrmann SA. Hip Abductor Weakness in Distance Runners with Iliotibial Band Syndrome. *Clinical Journal of Sports Medicine*. 2000;10:169-175.
33. Fullam K, Caulfield B, Coughlan GF, Delahunt E. Kinematic analysis of selected reach directions of the Star Excursion Balance Test compared with the Y-Balance Test. *J Sport Rehabil*. 2014;23(1):27-35.
34. Gabriner ML, Houston MN, Kirby JL, Hoch MC. Contributing factors to star excursion balance test performance in individuals with chronic ankle instability. *Gait Posture*. 2015;41(4):912-916.
35. Garrison JCB, Jim; Cohen, Kiley; Conway, John. Effects of hip strengthening on early outcomes following anterior cruciate ligament reconstruction. *International Journal of Sports Physical Therapy*. 2014;9(2):157-167.

36. Giandolini M, Gimenez P, Temesi J, et al. Effect of the Fatigue Induced by a 110-km Ultramarathon on Tibial Impact Acceleration and Lower Leg Kinematics. *PLoS One*. 2016;11(3):e0151687.
37. Gonell AC, Romero JAP, Soler LM. Relationship Between The Y Balance Test Scores and Soft Tissue Injury Incidence in a Soccer Team. *International Journal of Sports Physical Therapy*. 2015;10(7):955-966.
39. Gribble PA, Kelly SE, Refshauge KM, Hiller CE. Interrater reliability of the star excursion balance test. *J Athl Train*. 2013;48(5):621-626.
40. Gribble PA, Terada M, Beard MQ, et al. Prediction of Lateral Ankle Sprains in Football Players Based on Clinical Tests and Body Mass Index. *Am J Sports Med*. 2016;44(2):460-467.
41. Gribble PAH, Jay; Denegar, Craig. R.; Buckley William E. The Effects of Fatigue and Chronic Ankle Instability on Dynamic Postural Control. *Journal of Athletic Training*. 2004;39(4):321-329.
42. Hale SA, Hertel J, Olmsted-Kramer LC. The effect of a 4-week comprehensive rehabilitation program on postural control and lower extremity function in individuals with chronic ankle instability. *J Orthop Sports Phys Ther*. 2007;37(6):303-311.
43. Hall EA, Docherty CL, Simon J, Kingma JJ, Klossner JC. Strength-training protocols to improve deficits in participants with chronic ankle instability: a randomized controlled trial. *J Athl Train*. 2015;50(1):36-44.
44. Hamill J, Miller R, Noehren B, Davis I. A prospective study of iliotibial band strain in runners. *Clin Biomech (Bristol, Avon)*. 2008;23(8):1018-1025.
46. Hartley EM, Hoch MC, Boling MC. Y-balance test performance and BMI are associated with ankle sprain injury in collegiate male athletes. *J Sci Med Sport*. 2018;21(7):676-680.
47. Hertel JB, Rebecca A.; Hale, Sheri A.; Olmsted-Kramer, Lauren C. Simplifying the Star Excursion Balance Test: Analyses of Subjects With and Without Chronic

Ankle Instability. *Journal of Orthopaedic and Sports Physical Therapy*. 2006(36):131-137.

49. Hoch MC, Gaven SL, Weinhandl JT. Kinematic predictors of star excursion balance test performance in individuals with chronic ankle instability. *Clin Biomech (Bristol, Avon)*. 2016;35:37-41.
51. Hollman JHG, Barbara E.; Kozuchowski, Jakub; Vaughn, Amanda S.; Krause, David A.; Youdas, James W. Relationships Between Knee Valgus, Hip-Muscle Strength, and Hip-Muscle Recruitment During a Single-Limb Step-Down. *Journal of Sport Rehabilitation*. 2009;18(1):104-117.
52. Hooper TL, James CR, Brismee JM, et al. Dynamic balance as measured by the Y-Balance Test is reduced in individuals with low back pain: A cross-sectional comparative study. *Phys Ther Sport*. 2016;22:29-34.
53. Hotta T, Nishiguchi S, Fukutani N, et al. Functional Movement Screen for Predicting Running Injuries in 18-to-24-Year-Old Competitive Male Runners. *Journal of Strength and Conditioning Research*. 2015;29(10):2808-2815.
56. Hubbard TJ, Kramer LC, Denegar CR, Hertel J. Contributing factors to chronic ankle instability. *Foot Ankle Int*. 2007;28(3):343-354.
57. Hubbard TJK, Lauren C.; Denegar, Craig R.; Hertel, Jay. Correlations Among Multiple Measures of Functional and Mechanical Instability in Subjects With Chronic Ankle Instability. *Journal of Athletic Training*. 2007;42(3):361-366.
58. Ireland MLW, John D.; Ballantyne, Bryon T.; Davis, Irene M. Hip Strength in Females With and Without Patellofemoral Pain. *Journal of Orthopaedic and Sports Physical Therapy*. 2003;33(11):671-676.
60. Kang MH, Kim GM, Kwon OY, Weon JH, Oh JS, An DH. Relationship Between the Kinematics of the Trunk and Lower Extremity and Performance on the Y-Balance Test. *PM&R*. 2015;7(11):1152-1158.
61. Kaya D, Citaker S, Kerimoglu U, et al. Women with patellofemoral pain syndrome have quadriceps femoris volume and strength deficiency. *Knee Surg Sports Traumatol Arthrosc*. 2011;19(2):242-247.

62. Kinzey SJA, Charles W. The Reliability of the Star-Excursion Test in Assessing Dynamic Balance. *Journal of Orthopaedic and Sports Physical Therapy*. 1998;27(5):356-361.
65. Kuhman DJ, Paquette MR, Peel SA, Melcher DA. Comparison of ankle kinematics and ground reaction forces between prospectively injured and uninjured collegiate cross country runners. *Hum Mov Sci*. 2016;47:9-15.
66. Lai WC, Wang D, Chen JB, Vail J, Rugg CM, Hame SL. Lower Quarter Y-Balance Test Scores and Lower Extremity Injury in NCAA Division I Athletes. *Orthop J Sports Med*. 2017;5(8):2325967117723666.
67. Lawrence EL, Cesar GM, Bromfield MR, Peterson R, Valero-Cuevas FJ, Sigward SM. Strength, Multijoint Coordination, and Sensorimotor Processing Are Independent Contributors to Overall Balance Ability. *Biomed Res Int*. 2015;2015:561243.
69. Lee M, Sim S, Jiemin Y. Y-balance test but not functional movement screen scores are associated with peak knee valgus moments during unplanned sidestepping: implications for assessing anterior cruciate ligament injury risk. Paper presented at: International Society of Biomechanics in Sports2017.
74. Linek P, Booysen N, Sikora D, Stokes M. Functional movement screen and Y balance tests in adolescent footballers with hip/groin symptoms. *Phys Ther Sport*. 2019;39:99-106.
75. Lohse KR, Sherwood DE, Healy AF. How changing the focus of attention affects performance, kinematics, and electromyography in dart throwing. *Hum Mov Sci*. 2010;29(4):542-555.
77. Magrum E, Wilder RP. Evaluation of the injured runner. *Clin Sports Med*. 2010;29(3):331-345.
78. Mayer SW, Queen RM, Taylor D, et al. Functional Testing Differences in Anterior Cruciate Ligament Reconstruction Patients Released Versus Not Released to Return to Sport. *Am J Sports Med*. 2015;43(7):1648-1655.

80. McCann RS, Crossett ID, Terada M, Kosik KB, Bolding BA, Gribble PA. Hip strength and star excursion balance test deficits of patients with chronic ankle instability. *J Sci Med Sport*. 2017;20(11):992-996.
82. Messier SP, Martin DF, Mihalko SL, et al. A 2-Year Prospective Cohort Study of Overuse Running Injuries: The Runners and Injury Longitudinal Study (TRAILS). *Am J Sports Med*. 2018;46(9):2211-2221.
84. Milner CE, Ferber R, Pollard CD, Hamill J, Davis IS. Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc*. 2006;38(2):323-328.
85. Moran RW, Schneiders AG, Mason J, Sullivan SJ. Do Functional Movement Screen (FMS) composite scores predict subsequent injury? A systematic review with meta-analysis. *Br J Sports Med*. 2017;51(23):1661-1669.
86. Napier C, MacLean CL, Maurer J, Taunton JE, Hunt MA. Kinetic risk factors of running-related injuries in female recreational runners. *Scand J Med Sci Sports*. 2018;28(10):2164-2172.
88. Noehren B, Davis I, Hamill J. ASB clinical biomechanics award winner 2006 prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clin Biomech (Bristol, Avon)*. 2007;22(9):951-956.
89. Noehren B, Hamill J, Davis I. Prospective evidence for a hip etiology in patellofemoral pain. *Med Sci Sports Exerc*. 2013;45(6):1120-1124.
90. Noehren B, Pohl MB, Sanchez Z, Cunningham T, Lattermann C. Proximal and distal kinematics in female runners with patellofemoral pain. *Clin Biomech (Bristol, Avon)*. 2012;27(4):366-371.
91. Noehren B, Schmitz A, Hempel R, Westlake C, Black W. Assessment of strength, flexibility, and running mechanics in men with iliotibial band syndrome. *J Orthop Sports Phys Ther*. 2014;44(3):217-222.
92. Norris BT-J, E. Hip- and Thigh-Muscle Activation During the Star Excursion Balance Test. *Journal of Sport Rehabilitation*. 2011;20:428-441.

93. Olmsted LC, Carcia CR, Hertel J, Shultz SJ. Efficacy of the Star Excursion Balance Tests in Detecting Reach Deficits in Subjects With Chronic Ankle Instability. *Journal of Athletic Training*. 2002;37(4):501-506.
95. Paquette MR, Melcher DA. Impact of a Long Run on Injury-Related Biomechanics with Relation to Weekly Mileage in Trained Male Runners. *J Appl Biomech*. 2017;33(3):216-221.
96. Payne S, McCabe M, Pulliam J. The Effect of Chronic Ankle Instability (CAI) on Y-Balance Scores in Soccer Athletes. *Journal of Sports Medicine and Allied Health Sciences: Official Journal of the Ohio Athletic Trainers Association*. 2016;2(1).
97. Piva SRG, Edward A.; Childs, John D. Strength Around the Hip and Flexibility of Soft Tissues in Individuals With and Without Patellofemoral Pain Syndrome. *Journal of Orthopaedic and Sports Physical Therapy*. 2005;35(12):793-801.
98. Plisky Pea. Star Excursion Balance Test as a Predictor of Lower Extremity Injury in High School Basketball Players. *Journal of Orthopaedic and Sports Physical Therapy*. 2006;36(12):911-919.
99. Plisky PG, Paul P.; Butler, Robert J.; Kiesel, Kyle B.; Underwood, Frank B.; Elkins, Bryant. The Reliability of an Instrumented Device for Measuring Components of the Star Excursion Balance Test. *North American Journal of Sports Physical Therapy*. 2009;4(2):92-99.
100. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star Excursion Balance Test as a Predictor of Lower Extremity Injury in High School Basketball Players. *Journal of Orthopaedic and Sports Physical Therapy*. 2006;36(12):911-919.
101. Powers CM. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *J Orthop Sports Phys Ther*. 2010;40(2):42-51.
103. Radzak KN, Putnam AM, Tamura K, Hetzler RK, Stickley CD. Asymmetry between lower limbs during rested and fatigued state running gait in healthy individuals. *Gait Posture*. 2017;51:268-274.
104. Ramskov D, Barton C, Nielsen RO, Rasmussen S. High eccentric hip abduction strength reduces the risk of developing patellofemoral pain among novice runners

initiating a self-structured running program: a 1-year observational study. *J Orthop Sports Phys Ther.* 2015;45(3):153-161.

107. Smith CA, Chimera NJ, Warren M. Association of y balance test reach asymmetry and injury in division I athletes. *Med Sci Sports Exerc.* 2015;47(1):136-141.
109. Souza RB, Powers CM. Predictors of hip internal rotation during running: an evaluation of hip strength and femoral structure in women with and without patellofemoral pain. *Am J Sports Med.* 2009;37(3):579-587.
110. Stefanyshyn DJ, Stergiou P, Lun VM, Meeuwisse WH, Worobets JT. Knee angular impulse as a predictor of patellofemoral pain in runners. *Am J Sports Med.* 2006;34(11):1844-1851.
112. Stiffler MR, Bell DR, Sanfilippo JL, Hetzel SJ, Pickett KA, Heiderscheid BC. Star Excursion Balance Test Anterior Asymmetry Is Associated With Injury Status in Division I Collegiate Athletes. *J Orthop Sports Phys Ther.* 2017;47(5):339-346.
113. Taunton JER, M. B.; Clement, D. B.; McKenzie, D.C.; Lloyd-Smith, D. R.; Zumbo, B. D. A retrospective case-control analysis of 2002 running injuries. *Br J Sports Med.* 2002;36:95-101.
116. Thijs Y, De Clercq D, Roosen P, Witvrouw E. Gait-related intrinsic risk factors for patellofemoral pain in novice recreational runners. *Br J Sports Med.* 2008;42(6):466-471.
117. Thijs Y, Pattyn E, Van Tiggelen D, Rombaut L, Witvrouw E. Is hip muscle weakness a predisposing factor for patellofemoral pain in female novice runners? A prospective study. *Am J Sports Med.* 2011;39(9):1877-1882.
120. Vitale JA, Torre AL, Banfi G, Bonato M. Effects of an 8-week body-weight neuromuscular training on dynamic balance and vertical jump performances in elite junior skiing athletes: A randomized controlled trial. *Journal of Strength and Conditioning Research.* 2018;32(4):911-920.
121. Vogler JH, Csiernik AJ, Yorgey MK, Harrison JJ, Games KE. Clinician-Friendly Physical Performance Tests for the Hip, Ankle, and Foot. *J Athl Train.* 2017;52(9):861-862.

125. Wen DY. Risk Factors for Overuse Injuries in Runners. *Current Sports Medicine Reports*. 2007;6(5):307-313.
127. Willy RW, Davis IS. The effect of a hip-strengthening program on mechanics during running and during a single-leg squat. *J Orthop Sports Phys Ther*. 2011;41(9):625-632.
128. Willy RW, Manal KT, Witvrouw EE, Davis IS. Are mechanics different between male and female runners with patellofemoral pain? *Med Sci Sports Exerc*. 2012;44(11):2165-2171.
129. Wilson BR, Robertson KE, Burnham JM, Yonz MC, Ireland ML, Noehren B. The Relationship Between Hip Strength and the Y Balance Test. *J Sport Rehabil*. 2018;27(5):445-450.
130. Wright AA, Dischiavi SL, Smoliga JM, Taylor JB, Hegedus EJ. Association of Lower Quarter Y-Balance Test with lower extremity injury in NCAA Division 1 athletes: an independent validation study. *Physiotherapy*. 2017;103(2):231-236.

CHAPTER THREE

A MULTIVARIATE ANALYSIS BETWEEN THE Y-BALANCE TEST AND INJURY-LINKED RUNNING MECHANICS

Contribution of Authors and Co-Authors

Manuscript in Chapter 3

Author: Charles Scott Wilson

Contributions: Conceived the study, collected data, processed data, performed statistical analyses and wrote the manuscript.

Co-Author: Allison Theobold

Contributions: Provided consultation on statistical analyses.

Co-Author: Sara Skammer

Contributions: Assisted with subject recruitment, data collection and processing.

Co-Author: Sam Nelson

Contributions: Assisted with subject recruitment, data collection and processing

Co-Author: James Becker

Contributions: Conceived the study, collected data, performed statistical analyses and edited the manuscript.

Manuscript Information

Scott Wilson, Allison Theobald, Sara Skammer, Sam Nelson and James Becker

The American Journal of Sports Medicine

Status of Manuscript:

- ☒ Prepared for submission to a peer-reviewed journal
- ☐ Officially submitted to a peer-reviewed journal
- ☐ Accepted by a peer-reviewed journal
- ☐ Published in a peer-reviewed journal

ABSTRACT

Background: Running is a popular form of exercise and sport. Yet, unfortunately, running injuries are also highly common. The Y-Balance Test (YBT) has been used to measure strength, stability and neuromuscular control in multiple athletic populations. However, to our knowledge, it has not been evaluated in a population of distance runners.

Purpose: To examine the relationship between YBT performance and injury-linked running mechanics.

Study Design: Cross-sectional study.

Methods: 21 distance runners attended a single lab visit where kinematics of the YBT, and running kinematics and kinetics were recorded. 12 running variables previously linked to injury risk and YBT were calculated. Both sets of variables were compared using univariate and multivariate analysis.

Results: Linear regressions revealed no significant relationships between YBT composite score (CS) and running mechanics. However, multivariate analysis revealed a strong positive relationship between individual YBT reach directions and running mechanics. The running mechanics variables with the greatest contribution were the moments and impulses about the hip and knee. The remaining kinematic and kinetic variables displayed little to no contribution to the correlation.

Conclusion: YBT CS was not predictive of running mechanics previously linked to injury. However, individual reach directions may reflect abnormalities in frontal plane kinetics at the hip and knee.

Introduction

An estimated 40 million Americans participate in running at least one time each year, and up to 20 million run at least three days per week or more.⁸² Unfortunately, up to 79% of runners experience an injury within any one-year period,¹¹⁸ and over 50% of runners report experiencing multiple injuries.⁸² The majority of running injuries are overuse in nature, resulting from loads below the absolute strength threshold of a given tissue but applied repeatedly with insufficient recovery time between loading bouts.⁵⁴ Prospective studies have shown that many common running injuries are linked to specific kinematic or kinetic patterns such as increased hip adduction,^{88,89} knee internal rotation,⁸⁸ hip and knee abduction moments and impulses,^{26,110} and vertical loading rates.^{8,18} Reducing the overall incidence of running related injuries requires identifying individuals who display these movement patterns, and thus may be at a higher risk for injury, prior to injury occurrence. Currently, three-dimensional gait analysis is the gold standard for evaluating a runner's running mechanics. However, such analyses are not widely available due to facility costs and expertise or time required to perform such an analysis.

An alternative approach is to use clinical movement screens to evaluate a runner's overall neuromuscular control of their lower extremity. Clinical movement screens were developed to provide measures of strength, dynamic stability, and neuromuscular control of the lower extremity, and are easily performed in clinical or field settings.^{11,13,93} One of the most popular movement screens is called the Y-Balance Test (YBT),^{46,66} a derivative of the Star-Excursion Balance Test with improved inter and intra-rater reliability.^{14,99} Performing the YBT requires a participant to balance on one limb while the non-stance

limb reaches as far as possible anteriorly (ANT), posterior medially (PM), and posterior laterally (PL). The primary outcome is the distance reached in each direction, which can be normalized by leg length and used to calculate a composite score. While several studies have prospectively identified a relationship between YBT performance and injury across a variety of athletic populations,^{37,46,70,107} others have reported no relationships between YBT performance and subsequent injury.^{66,130} These discrepancies suggest additional work is needed to clarify relationships between YBT performance and injury.

Performance on the YBT is measured by a composite score that is calculated by taking the sum of the three reach distances and normalizing it to limb length.¹³ However, this method assumes that each reach direction carries equal weight in the evaluation of injury risk, and such oversimplifications have been criticized.⁸⁵ It has already been shown that different reach directions require different kinematic³³ and muscular coordination⁹² patterns. Several studies have also demonstrated that analyzing individual reach directions rather than composite score may be more useful in predicting injury.^{66,100} Thus, analyses of clinical movement screen performance should reflect the unique contributions of each component of the test. However, the statistical procedures used by many of the studies examining the relationship between YBT performance and injury do not consider the magnitudes of the contribution from each reach direction.^{60,66,96}

To date, most studies on the YBT have focused on multi-directional sports such as football,⁴⁰ or soccer,³⁷ but have not focused on unidirectional sports such as running. However, the YBT may be especially appropriate for assessing runners, given that high levels of performance on both the YBT and while running require neuromuscular control

of the hips and pelvis. Previous studies have shown strong positive correlations between YBT performance and strength of the muscle groups around the hip and knee in both healthy,^{122,129} and clinical^{47,80} populations. Neuromuscular control of the hip and pelvis are also essential for running, as weakness in the hip musculature has been associated with an increased risk of developing running related injuries in both retrospective^{31,91} and prospective studies,^{71,104} and is an important factor in optimizing running performance.^{48,83}

These similarities suggest the YBT may be an especially good screen for assessing runners' neuromuscular control of their lower extremity. If associations between performance on clinical movement screens such as the YBT and running mechanics were known, then this would allow clinicians to use a clinical movement screens to evaluate running biomechanics in settings where a full gait analysis is not available. Therefore, the purpose of this study was to describe the relationship between performance on the YBT and injury-related running mechanics in distance runners. More specifically, this study describes the association between performance on the individual reach directions of the YBT and the kinematic and kinetic variables which have been prospectively linked to development of running injuries. It was hypothesized that runners who performed worse on the YBT, as measured by reduced reach distances, would display greater magnitudes of injury-related running mechanics.

Materials and Methods

Participants

21 individuals volunteered to participate in this study (sex: 12M, 9F; age: 24.33 ± 7.61 years; mass: 61.32 ± 10.14 kg; height: 172.46 ± 9.30 cm) and were enrolled between August 2018 and March 2019. Participants were all highly trained runners (mean weekly running mileage: 50.76 ± 21.92 miles) from a collegiate Division I track and field team and from the surrounding community. All participants self-reported no injuries within three months prior to testing, maintained a running volume of at least 20 miles per week, and reported no injuries in the three months prior to data collection. Prior to participating all participants were provided written informed consent, and all procedures for this study were reviewed and approved by the Institutional Review Board of the affiliated university.

Experimental Protocol

This study was performed in a biomechanics laboratory containing two simultaneous data capture spaces immediately adjacent to each other. In one space, whole body kinematics were recorded using a 6-camera motion capture system (Motion Analysis Corp., Rohnert Park, CA) sampling at 200 Hz while participants ran on an instrumented treadmill (Treadmetrix, Salt Lake City, UT) sampling at 1000 Hz. In the second space, kinematics during the YBT were recorded using a 10-camera motion capture system (Motion Analysis Corp., Rohnert Park, CA), also sampling at 200 Hz. The order in which participants performed YBT and running trials was randomized to control for fatigue.

For the running trials, participants first completed a five-minute warmup at a self-selected pace. Sixty seconds of kinematic and kinetic data was then collected while participants ran at a pace matching their self-reported easy training run pace. Participants wore their personal running shoes for the study. All participants wore shoes which would be classified as traditional running shoes, with no participants using minimalist or maximalist shoes. For the YBT trials, participants were provided with verbal instructions and a visual demonstration of how to perform the test. Following these instructions, participants were permitted two practice trials. Corrective feedback was provided if needed. Participants then performed the YBT on the dominant limb, which was identified by asking the participant which limb they would use to “kick a ball.” The YBT was performed using a taped outline on the floor to specify the reach directions (Figure 1).

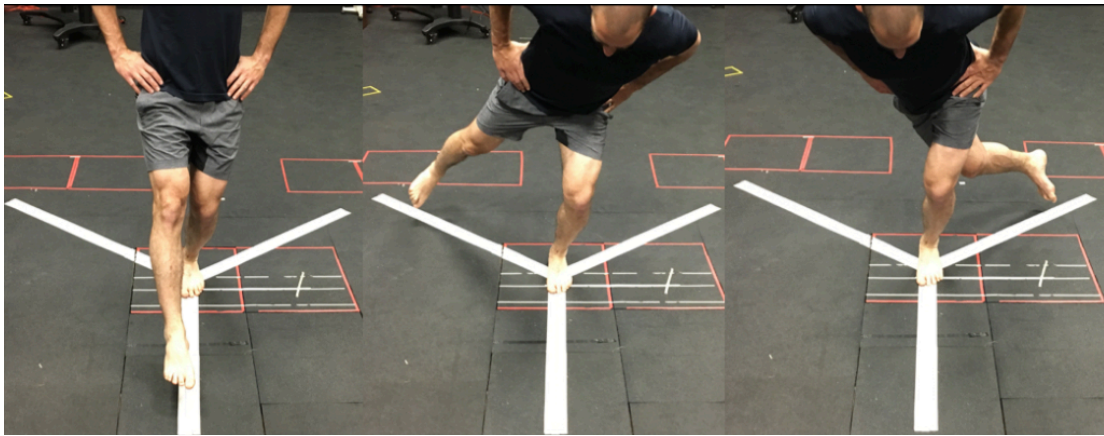


Figure 1. YBT reaches performed in the anterior (ANT), posterior-medial (PM) and posterior-lateral (PL) directions (left to right).

For both YBT and running trials reflective markers were placed bilaterally on the following bony landmarks: acromion process, medial and lateral humeral epicondyles, radial and ulnar styloid processes, anterior and posterior superior iliac spines, medial and

lateral femoral epicondyles, and medial and lateral malleoli. Additional tracking markers were placed on a headband worn by participants, the sternal notch, C7 spinous process, iliac crests, and clusters of four markers on the thigh and shank. The running trials were performed in the participants' shoes while the YBT trials were performed barefoot. Therefore, the marker placements were slightly different. For running trials three markers were on the heel counter, one on the lateral aspect and two on the vertical bisection. Additional tracking markers were placed on the heads and bases of the 1st and 5th metatarsals and the head of the 2nd metatarsal. For YBT trials foot markers were placed on the 1st, 2nd, and 5th metatarsal heads, and posterior aspect of the calcaneus. Prior to both running and YBT, a static trial was recorded after which the medial malleoli and femoral epicondyle markers were removed.

Data Analysis

All raw data was exported to Visual 3D (C-Motion, Inc., Germantown MD) for processing. For both running and YBT trials, marker trajectories were filtered using 4th-order, zero lag Butterworth filters, with cutoff frequencies of 8 Hz and 6 Hz, respectively. Ground reaction forces during running trials were filtered twice, also using 4th order, zero lag Butterworth filters, with the first filter having a cutoff frequency of 25 Hz and the second frequency of 15 Hz. The first was used to calculate loading related variables while the second was used to calculate joint moments.⁶⁴ Segment anatomic coordinate systems were established according to conventions from the International Society of Biomechanics¹³¹ and joint angles were calculated using a Cardan rotation sequence corresponding to flexion/extension, ab/adduction, and axial rotation. Joint moments were

calculated using Newtonian/Euler inverse dynamics and expressed as internal joint moments in the coordinate system of the proximal segment. Twenty consecutive gait cycles from the middle of the trials were extracted for analysis, with stance phase being defined using a 50 N threshold in the vertical ground reaction force. Twelve kinematic and kinetic variables previously linked to running injuries (Table 1) were calculated for each stance phase and then averaged within each participant.

Table 1. Kinematic and kinetic running gait variables of interest. Variables were selected based on being previously linked to running injuries in the cited studies.

Kinematic Variables	Kinetic Variables
Peak hip adduction ($^{\circ}$) ⁸⁷	Peak vertical loading rate ($\text{BW} \cdot \text{s}^{-1}$) ⁸⁴
Peak hip internal rotation ($^{\circ}$) ⁸⁷	Peak hip abductor moment (Nm/kg) ²⁶
Peak knee flexion ($^{\circ}$) ⁹⁵	Peak hip abductor impulse ($\text{Nm/kg} \cdot \text{s}^{-1}$) ²⁶
Peak knee adduction ($^{\circ}$) ⁹¹	Peak knee abductor moment (Nm/kg) ¹¹⁰
Peak eversion ($^{\circ}$) ⁴	Peak knee abductor impulse ($\text{Nm/kg} \cdot \text{s}^{-1}$) ¹¹⁰
Peak eversion ROM ($^{\circ}$) ⁶⁵	
Peak eversion velocity (m/s) ⁶⁵	

YBT trials were also processed in Visual 3D. The distance between the 2nd metatarsal head markers were used to calculate maximum reach distances in the ANT, PM, and PL directions. A YBT composite score was then calculated by normalizing the average of the three reach directions to stance limb length. Stance leg length was measured as the distance from the anterior-superior iliac spine to the medial malleolus when standing fully upright in the static trials. YBT performance data were derived from reach distances measured during a successful YBT trial. However, if participants did not maintain hands on the hips, touched down with the reach foot prior to maximal reach or used the reach foot for support the trial was discarded and repeated.

Statistical Analysis

Data were analyzed using univariate and multivariate analyses. The univariate analyses consisted of linear regressions between YBT composite scores and each of the 12 running gait variables. To control for Type I error the Benjamini-Hochberg procedure was used to calculate critical alpha values for each regression.⁶ Canonical correlation analysis (CCA) was used to describe the relationships between the three YBT reach directions and the 12 running gait variables for the dominant limb.

CCA was appropriate for the multivariate analysis as it describes the linear relationship between the multivariate measurements in two sets, here *Balance* and *Mechanics*. The *Balance* set of variables were comprised of the three YBT reach directions, each normalized to limb length, and the *Mechanics* set of variables were the 12 running gait variables. CCA finds “a pair of linear combinations—one from each of the two sets—such that the correlation between the two combinations is as large as possible.”¹⁰⁶ CCA describes the correlation between two sets of variables. Thus, the linear combinations associated with each set of variables contributes toward the canonical variable for that set. A CCA also maximizes not only the linearity between two canonical variables, but also between each canonical variable and its own subset of variables. The variables of each set were centered (to have a mean of 0) and scaled (to have a standard deviation of 1) prior to the CCA. The correlation between the resulting canonical variables was calculated using Pearson’s correlation coefficient. All statistical analyses were performed in R (R Core Team, 2020).

Results

Descriptive statistics for running and YBT variables are shown in Table 2. The univariate regressions revealed no statistically significant relationships between YBT composite score and any of the running mechanics variables (Figure 2).

Table 2. Descriptive statistics for YBT and running mechanics variables

Variable	Mean $\pm$ standard deviation
Peak hip adduction ($^{\circ}$)	10.72 ± 3.24
Peak hip internal rotation ($^{\circ}$)	9.87 ± 6.72
Peak knee flexion ($^{\circ}$)	34.85 ± 5.88
Peak knee adduction ($^{\circ}$)	4.05 ± 3.05
Peak eversion ($^{\circ}$)	9.11 ± 3.10
Peak eversion ROM ($^{\circ}$)	11.56 ± 3.97
Peak eversion velocity (m/s)	260.13 ± 65.62
Peak vertical loading rate ($BW \cdot s^{-1}$)	79.52 ± 23.22
Peak hip abductor moment (Nm/kg)	1.75 ± 0.52
Peak hip abductor impulse ($Nm/kg \cdot s^{-1}$)	0.20 ± 0.08
Peak knee abductor moment (Nm/kg)	0.85 ± 0.49
Peak knee abductor impulse ($Nm/kg \cdot s^{-1}$)	0.12 ± 0.12
YBT ANT reach (% limb length)	0.85 ± 0.06
YBT PL reach (% limb length)	0.84 ± 0.10
YBT PM reach (% limb length)	0.94 ± 0.07
YBT Composite score (% limb length)	0.88 ± 0.07

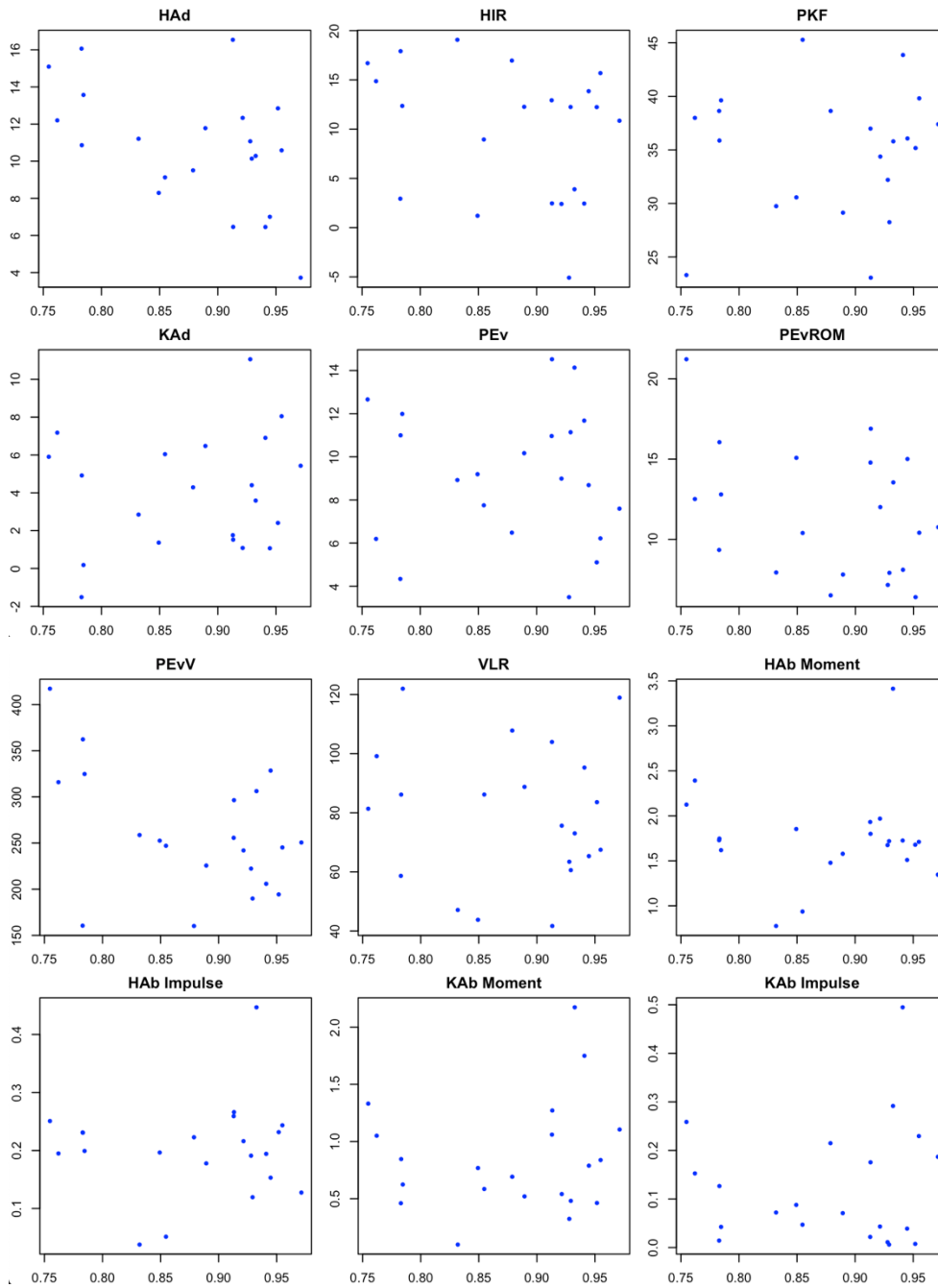


Figure 2. Individual regressions of YBT composite score as percent of leg length (x axis) and individual running gait variables. Top row from left to right: hip adduction (HAd), hip internal rotation (HIR), peak knee flexion (PKF), peak knee adduction(KAd), peak rearfoot eversion (PEv), peak eversion range of motion (PEvROM), peak eversion velocity (PEvV), peak vertical loading rate (VLR), peak hip abductor moment (HAb Moment), peak hip abductor impulse (HAb Impulse), peak knee abductor moment (KAb Moment), peak knee abductor impulse (KAb Impulse).

The CCA revealed a strong positive relationship between the *Balance* and *Mechanics* variables ($r = 0.94$). Both ANT and PL reach distances contributed positively to the *Balance* canonical variable, while the PM reach distance contributed negatively. For the *Mechanics* canonical variable, there was minimal to no contribution from kinematic variables (CCA coefficients ranged from -0.03 to 0.052). From the kinetic variables, HAb Impulse was the largest positive contributor to the *Mechanics* canonical variable. Both HAb Moment and KAb Moment were negative contributors to the *Mechanics* variable while the remaining kinetic variable (VLR) did not contribute. CCA determines the weighted contribution of each individual variable to the canonical variable, even if that variable has little to no influence on the canonical variable. Thus, variables with a coefficient less than 0.1 were excluded from discussion.

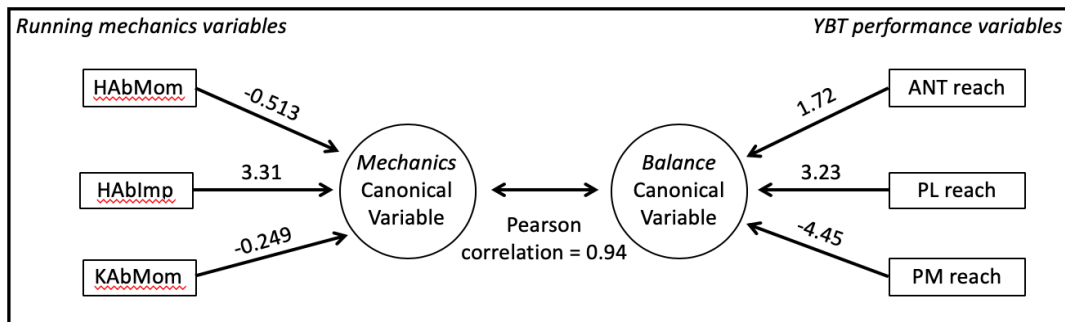


Figure 3. Graphical depiction of the final CCA model. The model only included variables with CCA coefficients greater than 0.1. Abbreviations are as follows: HAbMom: hip abductor

Discussion

The purpose of this study was to evaluate the relationship between YBT performance and running mechanics which have been previously linked to injury in

distance runners. Strength and neuromuscular control of the hip and pelvis are essential for both YBT performance and running injury prevention. Kinematic and muscular coordination patterns have also been shown to differ between reach directions. Thus, it was hypothesized that the individual reach directions of the YBT would display unique relationships to injury-linked running mechanics. Univariate linear regressions revealed no relationships between YBT composite score and any of the running mechanics. However, the multivariate CCA did reveal a strong relationship between YBT performance and injury-linked kinetics at the hip and knee while running.

The strongest contributors to the *Mechanics* canonical variable were the abductor moments and impulses at the hip and the abductor moment at the knee, suggesting that YBT performance is related to these variables while running. It is surprising that kinematics of the hip and knee did not contribute to the *Mechanics* canonical variable, given that hip and knee kinetics were such large contributors. The CCA indicated that further reaches in the ANT and PL directions were associated with an increase in the *Balance* canonical variable, with PL reach contributing two times as much compared to ANT. Considering that HAb Moments and KAb Moments were negative contributors to the *Mechanics* canonical variable, this suggests that greater ANT and PL reach is associated with a greater *Mechanics* variable, and thus lower peak HAb Moments and KAb Impulses while running, all other variables held constant. Higher values of these two variables have been reported in runners who prospectively develop patellofemoral pain syndrome, one of the most common running injuries.^{26,110} However, further research on these relationships is needed as external forces do not always correspond to *in vivo*

joint loads.^{32,123} Kinematic analysis of the YBT⁶⁰ and similar movement screens³³ have shown that control of the hip is critical for achieving larger reach distances in the PL and ANT and directions. Neuromuscular control at the hip is also critical during running to reduce the hip and knee abductor moments, as prospective studies have shown higher amounts of hip adduction in runners who subsequently get injured,^{88,89} and that high levels of eccentric hip abductor strength is protective against injury in novice runners.¹⁰⁴ Thus, the YBT may be a useful clinical screen to identify runners who may have difficulty controlling hip adduction during running and be at elevated risk for hip adduction related injuries. However, additional prospective studies are needed to further evaluate this hypothesis.

Previous studies have reported positive relationships between hip abductor, external rotator, and knee flexor strength and YBT performance, with stronger individuals having greater reach distances in ANT, PM, and PL directions, as well as higher composite scores.^{68,129} There are also relationships between hip abductor and external rotator strength and hip kinematics while running, with stronger runners displaying less hip adduction and hip internal rotation.^{45,114} Yet, the current study observed no relationships between YBT composite scores and hip adduction or internal rotation while running. Similarly, there were no relationships between YBT composite scores and of the ankle kinematic measures. Yet, performance on the YBT and similar movement screens identifies athletes who sustain ankle sprain injuries,^{40,46} differs between individuals with and without chronic ankle instability,^{47,80} and is better in those who use greater ankle frontal plane motion when performing the PL reach.⁶⁰

Several factors may explain the lack of relationships between YBT composite score and running kinematics. First, it may be that while the muscle groups utilized for neuromuscular control of the hip and pelvis during the two activities are similar, the tasks themselves are too different. Running is a dynamic task that requires the ability to resist cyclic ground reaction forces and impulses while continuing forward momentum. While the YBT also requires dynamic joint stability and eccentric strength, similar to running, the YBT is not repetitive in nature, does not require resisting cyclic loads, and is performed at much slower velocities. Thus, the movement strategies during the YBT may not necessarily carry over to running. Alternatively, the lack of relationships may be due to the use of the single composite score in the regressions. While single composite scores are common in several clinical movement screens, there is a growing body of evidence suggesting that individual reach scores are more informative for detecting variations in coordination patterns or predicting injury in multidirectional sports.^{85,107} The results of this study suggest this may also be true for unidirectional sports such as running. However, whether there are relationships between individual YBT reach directions and any running mechanical variables requires further investigation.

While the univariate analyses did not suggest relationships between YBT performance and running mechanics, the multivariate CCA displayed a strong positive relationship between *Balance* and *Mechanics* canonical variables. The PM reach direction was the greatest contributor to the *Balance* canonical variable, but was associated with a decrease in *Balance*. The opposite was seen for the ANT and PL reach directions as they contributed positively to the *Balance* canonical variable. One possible

explanation for the different relationships between reach directions is that muscular activation and coordination differs between the directions. Specifically, activation of the vastus lateralis and vastus medialis are greatest in the ANT reach direction, while semitendinosus and biceps femoris activity is greatest in the posterior directions, and gastrocnemius activation is similar between directions.²⁴ Additionally, activation of the gluteus medius is lowest in the PM direction while gluteus maximus activation is not different across directions.⁹² These differences in muscle activity between reach directions suggest that muscles are contributing differently to controlling the whole body center of mass motion based on the direction of the reach. While this requires further investigation to confirm, it may explain the opposing contributions of the ANT, PL, and PM direction to the *Balance* canonical variable. and their subsequent relationship to running mechanics.

There are several limitations to consider when interpreting the results of this study. First, and perhaps most importantly, is that all participants in the current study were healthy at the time of testing. Thus, we cannot determine whether the relationships between YBT performance and running mechanics identified in the current study are predictive of injury or would be similar if injured participants were evaluated. While previous studies have shown that injured individuals perform differently on the YBT than healthy controls,^{47,49,52,80} the participants in these studies were already injured at the time of testing. Thus, it is unclear whether the differences in YBT performance caused or were an accommodation to the injury. Second, beyond not being currently injured or having a lower extremity injury in the three months prior to testing, we did not control for injury

history. Previous studies have shown that injury history also influences YBT performance,¹³ and thus may have influenced the relationships observed in the current study.

There are also methodological limitations to consider. Participants performed the running trials in their own shoes but completed the YBT trials barefoot. This was done because the YBT was part of a larger preseason clinical assessment. While there is a large body of literature demonstrating that footwear influences running mechanics,^{30,115} it is currently unknown whether footwear influences performance on the YBT. If so, then the relationships observed in the current study may only be true if the YBT is performed barefoot and differ if the YBT is performed in shoes. Second, although the order in which participants ran or performed YBT was randomized, they all performed the YBT in a relatively fresh state, and, given their training history, the amount of running performed was not likely to overly fatigue them. It has been shown that performance on the YBT worsens when performed in a fatigued state.⁵⁹ Thus, whether the relationships observed in the current study remain if the YBT is performed in a fatigued state requires further investigation. Foot strike pattern was not controlled, and different foot strike patterns can influence ground reaction forces.¹⁰⁵ Finally, we also did not control running speed during the trials, allowing participants to run at a pace they felt matched their easy training run speed. Many of the kinematic and kinetic variables assessed during the running trials vary with speed, and thus the relationship between YBT and running mechanics may depend on running speed. Lastly, the participants in this study were well-trained runners from the surrounding community and were not randomly selected. Thus, these results may only

apply to runners of a similar age range and training status in the region. Further, due to the observational nature of the study we cannot infer that the kinetic variables at the hip and knee while running were directly related to YBT performance.

Conclusions

In summary, this study evaluated the relationships between performance on the YBT and running kinematics and kinetics. Our results show that when evaluated using a single composite score, YBT performance does not provide insight into running mechanics. However, multivariate analysis using individual YBT reach directions revealed a strong relationship between YBT performance and running mechanics. Specifically, abductor moments and impulses at the hip and knee contributed the greatest to the *Mechanics* canonical variable, which was strongly correlated with the *Balance* canonical variable. Prospective studies have also shown these variables are related to the development of running injuries. Thus, the YBT may be a useful clinical screen for identifying runners who have difficulty control hip motion while running. However, prospective studies are required to determine whether YBT performance is predictive for the development of running injuries.

REFERENCES CITED

4. Becker J, James S, Wayner R, Osternig L, Chou LS. Biomechanical Factors Associated With Achilles Tendinopathy and Medial Tibial Stress Syndrome in Runners. *Am J Sports Med.* 2017;45(11):2614-2621.
6. Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *JR Stat Soc B.* 1995;57(1):289-300.
8. Bredeweg SW, Buist I, Kluitenberg B. Differences in kinetic variables between injured and noninjured novice runners: a prospective cohort study. *J Sci Med Sport.* 2013;16(3):205-210.
11. Butler RJ, Bullock G, Arnold T, Plisky P, Queen R. Competition-Level Differences on the Lower Quarter Y-Balance Test in Baseball Players. *J Athl Train.* 2016;51(12):997-1002.
13. Chimera NJ, Smith CA, Warren M. Injury history, sex, and performance on the functional movement screen and Y balance test. *J Athl Train.* 2015;50(5):475-485.
14. Chimera NJ, Warren M. Use of clinical movement screening tests to predict injury in sport. *World J Orthop.* 2016;7(4):202-217.
18. Davis IS, Bowser BJ, Mullineaux DR. Greater vertical impact loading in female runners with medically diagnosed injuries: a prospective investigation. *Br J Sports Med.* 2016;50(14):887-892.
24. Earl JH, Jay. Lower-Extremity Muscle Activation During the Star Excursion Balance Tests. *J Sport Rehabil.* 2001;10:93-104.
26. Eskofier BM, Kraus M, Worobets JT, Stefanyshyn DJ, Nigg BM. Pattern classification of kinematic and kinetic running data to distinguish gender, shod/barefoot and injury groups with feature ranking. *Comput Methods Biomech Biomed Engin.* 2012;15(5):467-474.
30. Frederick EC. Kinematically mediated effects of sport shoe design: a review. *J Sports Sci.* 1986;4(3):169-184.

31. Fredericson M, Cookingham CL, Chaudhari AM, Dowell BC, Oestreich N, Sahrmann SA. Hip Abductor Weakness in Distance Runners with Iliotibial Band Syndrome. *Clinical Journal of Sports Medicine*. 2000;10:169-175.
32. Fregly BJ, Besier TF, Lloyd DG, et al. Grand challenge competition to predict in vivo knee loads. *J Orthop Res*. 2012;30(4):503-513.
33. Fullam K, Caulfield B, Coughlan GF, Delahunt E. Kinematic analysis of selected reach directions of the Star Excursion Balance Test compared with the Y-Balance Test. *J Sport Rehabil*. 2014;23(1):27-35.
37. Gonell AC, Romero JAP, Soler LM. Relationship Between The Y Balance Test Scores and Soft Tissue Injury Incidence in a Soccer Team. *International Journal of Sports Physical Therapy*. 2015;10(7):955-966.
40. Gribble PA, Terada M, Beard MQ, et al. Prediction of Lateral Ankle Sprains in Football Players Based on Clinical Tests and Body Mass Index. *Am J Sports Med*. 2016;44(2):460-467.
45. Hannigan JJ, Osternig LR, Chou LS. Sex-Specific Relationships Between Hip Strength and Hip, Pelvis, and Trunk Kinematics in Healthy Runners. *J Appl Biomech*. 2018;34(1):76-81.
46. Hartley EM, Hoch MC, Boling MC. Y-balance test performance and BMI are associated with ankle sprain injury in collegiate male athletes. *J Sci Med Sport*. 2018;21(7):676-680.
47. Hertel JB, Rebecca A.; Hale, Sheri A.; Olmsted-Kramer, Lauren C. Simplifying the Star Excursion Balance Test: Analyses of Subjects With and Without Chronic Ankle Instability. *Journal of Orthopaedic and Sports Physical Therapy*. 2006(36):131-137.
48. Hickson RC, Dvorak BA, Gorostiaga EM, Kurowski TT, C. F. Potential for strength and endurance training to amplify endurance performance. *J Appl Physiol*. 1988;65:2285-2290.

49. Hoch MC, Gaven SL, Weinhandl JT. Kinematic predictors of star excursion balance test performance in individuals with chronic ankle instability. *Clin Biomech (Bristol, Avon)*. 2016;35:37-41.
52. Hooper TL, James CR, Brismee JM, et al. Dynamic balance as measured by the Y-Balance Test is reduced in individuals with low back pain: A cross-sectional comparative study. *Phys Ther Sport*. 2016;22:29-34.
54. Hreljac A. Impact and Overuse Injuries in Runners. *Medicine & Science in Sports & Exercise*. 2004:845-849.
59. Johnston W, Dolan K, Reid N, Coughlan GF, Caulfield B. Investigating the effects of maximal anaerobic fatigue on dynamic postural control using the Y-Balance Test. *J Sci Med Sport*. 2018;21(1):103-108.
60. Kang MH, Kim GM, Kwon OY, Weon JH, Oh JS, An DH. Relationship Between the Kinematics of the Trunk and Lower Extremity and Performance on the Y-Balance Test. *PM&R*. 2015;7(11):1152-1158.
64. Kristianslund E, Krosshaug T, van den Bogert AJ. Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention. *J Biomech*. 2012;45(4):666-671.
65. Kuhman DJ, Paquette MR, Peel SA, Melcher DA. Comparison of ankle kinematics and ground reaction forces between prospectively injured and uninjured collegiate cross country runners. *Hum Mov Sci*. 2016;47:9-15.
66. Lai WC, Wang D, Chen JB, Vail J, Rugg CM, Hame SL. Lower Quarter Y-Balance Test Scores and Lower Extremity Injury in NCAA Division I Athletes. *Orthop J Sports Med*. 2017;5(8):2325967117723666.
68. Lee DK, Kang MH, Lee TS, Oh JS. Relationships among the Y balance test, Berg Balance Scale, and lower limb strength in middle-aged and older females. *Braz J Phys Ther*. 2015;19(3):227-234.
70. Lehr ME, Plisky PJ, Butler RJ, Fink ML, Kiesel KB, Underwood FB. Field-expedient screening and injury risk algorithm categories as predictors of noncontact lower extremity injury. *Scand J Med Sci Sports*. 2013;23(4):e225-232.

71. Leudke LE, Heiderscheit BC, Williams DSB, Rauh MJ. Association of Isometric Strength of Hip and Knee Muscles with Injury Risk in High School Cross Country Runners. *International Journal of Sports Physical Therapy*. 2015;10(6):868-876.
80. McCann RS, Crossett ID, Terada M, Kosik KB, Bolding BA, Gribble PA. Hip strength and star excursion balance test deficits of patients with chronic ankle instability. *J Sci Med Sport*. 2017;20(11):992-996.
82. Messier SP, Martin DF, Mihalko SL, et al. A 2-Year Prospective Cohort Study of Overuse Running Injuries: The Runners and Injury Longitudinal Study (TRAILS). *Am J Sports Med*. 2018;46(9):2211-2221.
83. Mikkola J, Rusko H, Nummela A, Pollari T, Hakkinen K. Concurrent endurance and explosive type strength training improves neuromuscular and anaerobic characteristics in young distance runners. *Int J Sports Med*. 2007;28(7):602-611.
84. Milner CE, Ferber R, Pollard CD, Hamill J, Davis IS. Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc*. 2006;38(2):323-328.
85. Moran RW, Schneiders AG, Mason J, Sullivan SJ. Do Functional Movement Screen (FMS) composite scores predict subsequent injury? A systematic review with meta-analysis. *Br J Sports Med*. 2017;51(23):1661-1669.
87. Neal BS, Barton CJ, Gallie R, O'Halloran P, Morrissey D. Runners with patellofemoral pain have altered biomechanics which targeted interventions can modify: A systematic review and meta-analysis. *Gait Posture*. 2016;45:69-82.
88. Noehren B, Davis I, Hamill J. ASB clinical biomechanics award winner 2006 prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clin Biomech (Bristol, Avon)*. 2007;22(9):951-956.
89. Noehren B, Hamill J, Davis I. Prospective evidence for a hip etiology in patellofemoral pain. *Med Sci Sports Exerc*. 2013;45(6):1120-1124.
91. Noehren B, Schmitz A, Hempel R, Westlake C, Black W. Assessment of strength, flexibility, and running mechanics in men with iliotibial band syndrome. *J Orthop Sports Phys Ther*. 2014;44(3):217-222.

92. Norris BT-J, E. Hip- and Thigh-Muscle Activation During the Star Excursion Balance Test. *Journal of Sport Rehabilitation*. 2011;20:428-441.
93. Olmsted LC, Carcia CR, Hertel J, Shultz SJ. Efficacy of the Star Excursion Balance Tests in Detecting Reach Deficits in Subjects With Chronic Ankle Instability. *Journal of Athletic Training*. 2002;37(4):501-506.
95. Paquette MR, Melcher DA. Impact of a Long Run on Injury-Related Biomechanics with Relation to Weekly Mileage in Trained Male Runners. *J Appl Biomech*. 2017;33(3):216-221.
96. Payne S, McCabe M, Pulliam J. The Effect of Chronic Ankle Instability (CAI) on Y-Balance Scores in Soccer Athletes. *Journal of Sports Medicine and Allied Health Sciences: Official Journal of the Ohio Athletic Trainers Association*. 2016;2(1).
99. Plisky PG, Paul P.; Butler, Robert J.; Kiesel, Kyle B.; Underwood, Frank B.; Elkins, Bryant. The Reliability of an Instrumented Device for Measuring Components of the Star Excursion Balance Test. *North American Journal of Sports Physical Therapy*. 2009;4(2):92-99.
100. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star Excursion Balance Test as a Predictor of Lower Extremity Injury in High School Basketball Players. *Journal of Orthopaedic and Sports Physical Therapy*. 2006;36(12):911-919.
104. Ramskov D, Barton C, Nielsen RO, Rasmussen S. High eccentric hip abduction strength reduces the risk of developing patellofemoral pain among novice runners initiating a self-structured running program: a 1-year observational study. *J Orthop Sports Phys Ther*. 2015;45(3):153-161.
105. Rice HM, Jamison ST, Davis IS. Footwear matters: influence of footwear and foot strike on load rates during running. *Med Sci Sports Exerc*. 2016;48(12):2462-2468.
106. Schafer DWR, F. L. Exploratory Tools for Summarizing Multivariate Responses. In: Taylor M, ed. *The Statistical Sleuth: A Course in Methods of Data Analysis*. 3rd ed. Boston, MA: Brooks/Cole; 2013:514.
107. Smith CA, Chimera NJ, Warren M. Association of y balance test reach asymmetry and injury in division I athletes. *Med Sci Sports Exerc*. 2015;47(1):136-141.

110. Stefanyshyn DJ, Stergiou P, Lun VM, Meeuwisse WH, Worobets JT. Knee angular impulse as a predictor of patellofemoral pain in runners. *Am J Sports Med.* 2006;34(11):1844-1851.
114. Taylor-Haas JA, Hugentobler JA, DiCesare CA, et al. Reduced hip strength is associated with increased hip motion during running in young adult and adolescent male long-distance runners. *IJSPT.* 2014;9(4):456-467.
115. Theisen D, Malisoux L, Gette P, Nührenbörger C, Urhausen A. Footwear and running-related injuries – Running on faith? *Sports Orthopaedics and Traumatology Sport-Orthopädie - Sport-Traumatologie.* 2016;32(2):169-176.
118. Van Gent RN, Siem D, Van Middelkoop M, Van Os AG, Bierma-Zeinstra SM, Koes BW. Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. *Br J Sports Med.* 2007;41(8):469-480; discussion 480.
122. Walaszek RC, W.; Walaszek, K.; Burdacki, M.; Blaszczyk, J. Evaluation of the accuracy of the postural stability measurement with the Y-Balance Test based on levels of the biomechanical parameters. *Acta of Bioengineering and Biomechanics.* 2017;19(2):121-128.
123. Walter JP, D'Lima DD, Colwell CW, Jr., Fregly BJ. Decreased knee adduction moment does not guarantee decreased medial contact force during gait. *J Orthop Res.* 2010;28(10):1348-1354.
129. Wilson BR, Robertson KE, Burnham JM, Yonz MC, Ireland ML, Noehren B. The Relationship Between Hip Strength and the Y Balance Test. *J Sport Rehabil.* 2018;27(5):445-450.
130. Wright AA, Dischiavi SL, Smoliga JM, Taylor JB, Hegedus EJ. Association of Lower Quarter Y-Balance Test with lower extremity injury in NCAA Division 1 athletes: an independent validation study. *Physiotherapy.* 2017;103(2):231-236.
131. Wu G, Siegler S, Allard P, et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion - part I: ankle, hip, and spine. *J Biomech.* 2002;35:543-548.

CHAPTER FOUR

THE RELATIONSHIP BETWEEN Y-BALANCE TEST PERFORMANCE AND RUNNING MECHANICS AT THE HIP FOLLOWING FATIGUE

Contribution of Authors and Co-Authors

Manuscript in Chapter 4

Author: Charles Scott Wilson

Contributions: Conceived the study, collected data, processed data, performed statistical analyses and wrote the manuscript.

Co-Author: Sara Skammer

Contributions: Assisted with subject recruitment, data collection and processing.

Co-Author: Sam Nelson

Contributions: Assisted with subject recruitment, data collection and processing

Co-Author: James Becker

Contributions: Conceived the study and edited the manuscript.

Manuscript Information

Scott Wilson, Sam Nelson, Sara Skammer and James Becker

The Journal of Orthopedic and Sports Physical Therapy

Status of Manuscript:

 X Prepared for submission to a peer-reviewed journal

 Officially submitted to a peer-reviewed journal

 Accepted by a peer-reviewed journal

 Published in a peer-reviewed journal

ABSTRACT

Background: Running is a popular form of endurance exercise. However, fatigue-related changes in running mechanics may increase the risk of injury. The Y-Balance Test (YBT) has been used to predict injury in various athletic populations. Yet, to our knowledge, no studies have examined the relationships between YBT performance and changes in injury-linked running mechanics. **Purpose:** To examine the relationship between YBT performance and changes in injury-linked running mechanics at the hip along the course of a fatiguing run. **Study Design:** Cross-sectional study. **Methods:** 16 distance runners attended a single lab visit where YBT kinematics were recorded in a fresh state, while running kinematics and kinetics were recorded prior and following a run to volitional fatigue. Percent change was then calculated for the four running variables at the hip. Paired t-tests were used to compare running mechanics between pre and post fatigue conditions. Percent change in the running mechanics variables was compared with performance on individual YBT reach directions and composite score (CS) using univariate analyses. **Results:** Running mechanics did not significantly change between the pre and post fatigue conditions. Linear regressions did not reveal any significant relationships between YBT performance and percent change in any of the kinematic or kinetic variables at the hip. **Conclusion:** Neither individual reach directions nor YBT CS predicted percent change in running mechanics.

Introduction

Running is a popular form of exercise with more than 20 million Americans regularly participating each year.¹⁸ Unfortunately, running injuries are common with 19.4 – 79.3% of runners experiencing injury in any given one-year period,¹¹⁸ and many runners experiencing multiple injuries.⁸² Most running injuries result from overuse^{82,125} and occur due to the repetitive applications of loads below the absolute strength threshold of a given tissue without sufficient time for recovery.⁵⁵ Abnormal kinematics and kinetics at the hip have been linked with several common running injuries. Specifically, increased hip adduction has been prospectively related to iliotibial-band syndrome⁸⁸ and patellofemoral pain,⁸⁹ while greater hip abductor moments have also been prospectively linked to patellofemoral pain.²⁶ Identification of these biomechanical patterns prior to injury may allow clinicians or coaches to design prevention programs that minimize injury risk. Currently, 3-D kinematic and kinetic analysis is the gold standard for evaluating running mechanics. However, access to such analyses are often limited by material cost, expertise and time. While 2-D gait analysis can be used to measure single-plane movement with high accuracy,⁷⁹ these analyses still require the presence of equipment such as a treadmill enough space to establish a sufficient field of view, and time for a clinician to perform the analysis. Clinics or coaches may not always have these resources at their disposal.

In contrast, clinical movement screens, are relatively inexpensive, require little space and can be performed in less time than it would take to conduct a 2-D analysis. Clinical movement screens provide measures of strength, dynamic joint stability and

neuromuscular control of the lower extremities.^{11,13,40,93} The Y-Balance Test (YBT) is one commonly used movement screen.^{37,46,66} Performing the YBT requires the participant to maintain a single-limb stance while reaching in the anterior (ANT), posterior-lateral (PL) and posterior-medial (PM) directions. A normalized composite score (CS) is calculated by dividing the sum of the reach distances by the stance-limb length. Studies have identified relationships between YBT performance and subsequent injury across a variety of sports. Gonell et al. reported that soccer players with a ≥ 4 cm difference in PM reach were almost four times more likely to sustain a non-contact injury.³⁷ Smith et al. also found that an ANT reach asymmetry ≥ 4 cm predicted injury in NCAA Division-I athletes.¹⁰⁷ Greater YBT reach scores have also been related to reduced peak knee valgus moments during sidestepping, suggesting that higher YBT performance may be associated with a reduced risk for anterior cruciate ligament injury.⁶⁹ Yet, to date, research on the YBT has predominantly involved multidirectional sports such as football,⁴⁰ soccer³⁷ or basketball¹⁰⁰, and it is unclear whether similar relationships would extend to uni-directional sports such as running.

The YBT may be an appropriate tool for evaluating runners since good YBT performance requires substantial strength and neuromuscular control of the hips. Wilson et al. reported that YBT performance was positively correlated with strength of the hip abductors, extensors and external rotators,¹²⁹ while Linek et al. reported that injury of the musculature surrounding the hip significantly impaired YBT performance.⁷⁴ Kang et al. showed that higher YBT reach scores were correlated with greater sagittal plane range of motion at the hip, but reduced frontal and transverse plane motion.⁶⁰ Further,

interventions designed to improve strength and neuromuscular control of the lower extremities have been demonstrated to increase YBT performance.^{5,120} Weakness of the muscles surrounding the hip have been linked to the development of common running injuries. Specifically, runners with iliotibial-band syndrome demonstrate weaker hip abductors³¹ and external rotators.⁹¹ Luedke et al. also found that high school runners with reduced isometric hip abductor strength were more likely to develop patellofemoral pain in the subsequent cross country season.⁷¹ Running relies on eccentric muscular strength to resist the loads applied during stance phase, and greater eccentric strength has also been linked to a lower risk of injury in runners. A prospective study by Ramskov et al. showed that runners with greater eccentric strength of the hip abductors had a reduced risk of developing patellofemoral pain.¹⁰⁴

Reduced hip strength may contribute to the development of abnormal mechanics along the course of a fatiguing run. Running long distances or to volitional fatigue can lead to biomechanical changes that may increase the risk of injury. Specifically, hip adduction angle⁹⁵ and hip angular impulse¹²⁶ have both been shown to increase following a fatiguing run. Runners with poor strength or neuromuscular control of the hip may experience larger changes, and thus be at higher risk of injury during fatiguing runs.^{26,88,89} However, to date, it is unknown whether YBT performance may predict changes in running mechanics during a fatiguing run. Therefore, the purpose of this study was to evaluate whether YBT performance in a fresh state could predict changes in injury-related running mechanics at the hip following a fatiguing run in distance runners. It was hypothesized that runners who perform worse on the YBT would display greater changes

in injury-linked kinematics and kinetics at the hip following a run to fatigue. The ability of the YBT to predict changes in running mechanics at the hip could provide a valuable tool for coaches and clinicians to use in prospectively mitigating injury risk.

Materials and Methods

Participants

16 individuals volunteered to participate in this study (sex: 9 M, 7 F; age: 28.75 ± 9.17 years; mass: 69.09 ± 9.83 kg; height: 172.56 ± 8.47 cm) and were enrolled between August 2019 and March 2020. Participants were experienced distance runners (mean weekly running mileage: 28.43 ± 15.64 miles) from the surrounding community. All participants self-reported no injuries and maintained a running volume of at least 20 miles per week within three months prior to testing. Prior to participating all participants were provided written informed consent, and all procedures for this study were reviewed and approved by the Institutional Review Board of the affiliated university.

Experimental Protocol

Upon arrival at the laboratory participants completed a short questionnaire detailing their history of running training. The questionnaire also identified the dominant limb which was described as the preferred limb used to “kick a ball.” Following the questionnaire subjects completed a five-minute warm-up run at a self-selected easy pace. After the warm-up participants were given verbal and visual demonstration of the YBT and subsequently performed two practice trials. Participants then completed two pre-run YBT trials, during which kinematic data were recorded. The YBT was performed on the

dominant limb, and the average of the two trials was used to calculate the YBT reach scores. If participants removed hands from the hips, touched down more than once during a reach or used the reach limb for significant support the trial was discarded and repeated. A taped outline of the YBT was used to specify the reach directions (Figure 1). Following the YBT trials participants ran at their self-selected easy pace while 30 seconds of kinematic and kinetic data were collected. Participants were then familiarized with the Borg 6-20 Rate of Perceived Exertion (RPE) scale and asked to run at a self-selected race pace until they reached a 17 (Very Hard). Similar running protocols have shown that kinematic or kinetic changes in running mechanics occur within 15 – 20 minutes of running.^{20,63} In order to stay within these time parameters the runners were asked to run at a pace estimated between their 3k and 5k race pace, and were allowed to incrementally increase their speed as needed. Following the run an additional 30 seconds of kinematic and kinetic data were collected at the participants' easy pace. Participants wore their personal running shoes for the running trial while the YBT was performed barefoot.

Both the YBT and running trials utilized a reflective marker set consisting of bilateral placements on the acromion process, anterior and posterior superior iliac spines, medial and lateral femoral epicondyles, and medial and lateral malleoli. Additional tracking markers were placed on the sternal notch, C7 spinous process, iliac crests and on the thigh and shank as four-marker clusters. The foot markerset for both running and YBT trials also included three markers on the heel counter, one on the lateral aspect and two on the vertical bisection. Additional tracking markers were placed on the heads and bases of the 1st and 5th metatarsals and the head of the 2nd metatarsal as well as the

navicular. Static trials were recorded for both the running and YBT trials after which the medial malleoli and femoral epicondyle markers were removed.

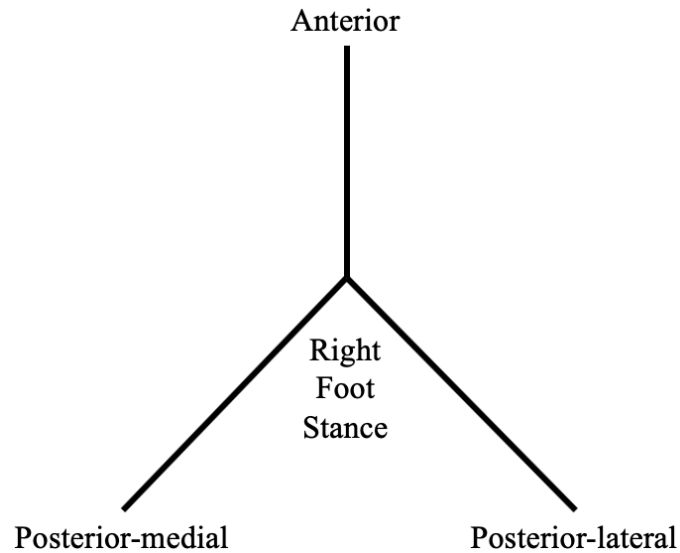


Figure 1. Visual depiction of the Y-Balance Test reach directions performed with right limb stance.

Data Analysis

Whole body kinematics for running were recorded using a 6-camera motion capture system (Motion Analysis Corp., Rohnert Park, CA) sampling at 200 Hz while participants ran on an instrumented treadmill (Treadmetrix, Salt Lake City, UT) sampling at 1000 Hz. Kinematics during the YBT were also recorded using the 6-camera motion capture system (Motion Analysis Corp., Rohnert Park, CA) sampling at 200 Hz. All raw kinematic was processed using Cortex (Motion Analysis Corp., Rohnert Park, CA). Marker trajectories were filtered using 4th-order, zero lag Butterworth filters with cutoff frequencies of 8 Hz and 6 Hz⁷³ for the running and YBT trials, respectively. Kinematic and kinetic data were then exported to Visual 3D (C-Motion, Inc., Germantown MD) for

further processing. To reduce artifacts in joint moments, ground reaction forces during running trials were filtered using a 4th-order, zero lag Butterworth filter at 8 Hz prior to calculating joint moments.⁶⁴ Segment anatomic coordinate systems were established according to conventions from the International Society of Biomechanics and joint angles were calculated using a Cardan rotation sequence corresponding to flexion/extension, ab/adduction, and axial rotation.¹³¹ Joint moments were calculated using Newtonian/Euler inverse dynamics and expressed as internal joint moments in the coordinate system of the proximal segment. Twenty consecutive gait cycles from the middle of the trials were extracted for analysis, with stance phase being defined using a 50 N threshold in the vertical ground reaction force. The running variables selected for analysis included peak hip adduction,^{88,89} peak hip internal rotation,⁹¹ peak hip abductor moment²⁶ and peak hip abductor impulse⁷⁶ during stance phase. Variables were selected based on being previously linked to running injuries in prospective studies. Percent change was calculated for each of the running variables by subtracting the post-fatigue measure from the pre-fatigue measure, then dividing the value by the pre-fatigue measure. The resulting value was then multiplied by 100.

Distance between the dominant and non-dominant 2nd metatarsal head markers were used to calculate maximum reach distances in the ANT, PM and PL directions. A composite score was calculated by normalizing the sum of the three reach directions to stance leg length. Leg length was measured as the distance from the anterior-superior iliac spine to the medial malleolus when standing fully upright in the static trials.

Statistical Analysis

Paired t-tests were used to compare running mechanics between the pre and post run conditions. A total of 16 linear regressions were used to compare the relationships between YBT performance and percent change of each of the running mechanics variables. The Benjamini-Hochberg procedure was applied to the regression outputs to control for Type I error.⁶

Results

Descriptive statistics for the running and YBT variables are summarized in Tables 1 and 2, respectively. Average run time to reach a 17 on the Borg RPE scale was 16.58 ± 6.23 minutes, and average starting pace during the fatigue protocol was 3.22 ± 0.33 m/s. Paired t-tests indicated that running mechanics did not significantly change between the pre and post conditions. The linear regressions revealed no statistically significant relationships between YBT performance and percent change of any of the running mechanics variables.

Table 1. Descriptive statistics for running mechanics variables. Percent change reflects the difference in running variables between pre and post run conditions.

Variables	Mean $\pm$ standard deviation
<i>Pre-fatigue</i>	
Peak hip adduction ($^{\circ}$)	10.13 $\pm$ 3.75
Peak hip internal rotation ($^{\circ}$)	7.01 $\pm$ 6.61
Peak hip abductor moment (Nm/kg)	1.83 $\pm$ 0.29
Peak hip abductor impulse (Nm/kg*s ⁻¹)	0.25 $\pm$ 0.06
<i>Post-fatigue</i>	
Peak hip adduction ($^{\circ}$)	10.02 $\pm$ 4.25
Peak hip internal rotation ($^{\circ}$)	6.58 $\pm$ 7.20
Peak hip abductor moment (Nm/kg)	1.81 $\pm$ 0.48
Peak hip abductor impulse (Nm/kg*s ⁻¹)	0.24 $\pm$ 0.12

Table 2. Percent change in running mechanics between pre and post-fatigue conditions.

Variables	Percent change (%)	
	Mean $\pm$ standard deviation	Cohen's <i>d</i>
Peak hip adduction ($^{\circ}$)	-3.29 $\pm$ 19.00	0.07
Peak hip internal rotation ($^{\circ}$)	-1.50 $\pm$ 64.26	0.33
Peak hip abductor moment (Nm/kg)	-0.73 $\pm$ 22.59	0.05
Peak hip abductor impulse (Nm/kg*s ⁻¹)	-5.67 $\pm$ 31.20	0.10

Table 3. Descriptive statistics for the dominant limb YBT.

Variables	Mean $\pm$ standard deviation
YBT ANT reach (% limb length)	0.68 $\pm$ 0.06
YBT PL reach (% limb length)	0.83 $\pm$ 0.10
YBT PM reach (% limb length)	0.95 $\pm$ 0.07
YBT CS (% limb length)	0.81 $\pm$ 0.07

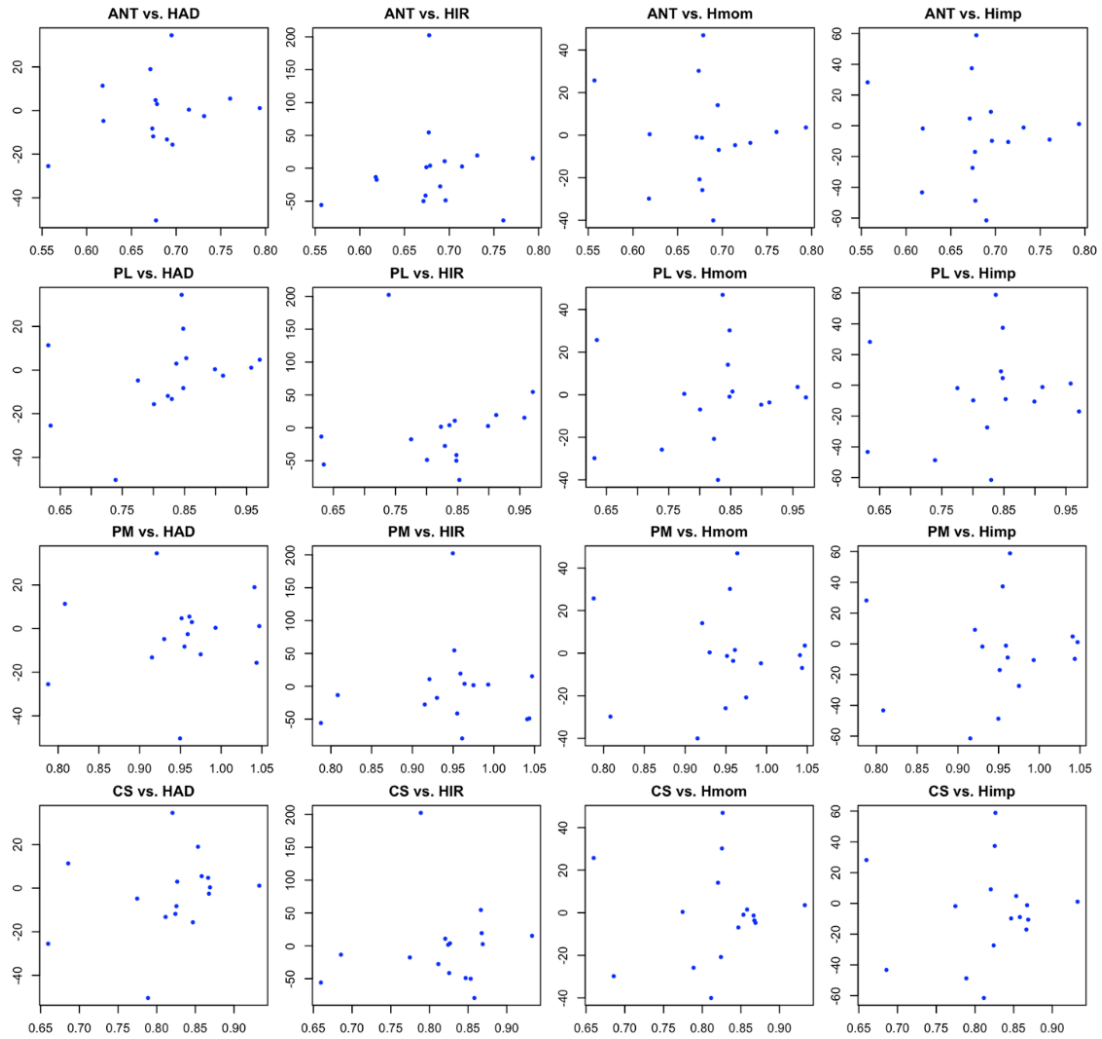


Figure 2. Individual regressions of YBT reach scores as percent of leg length (x axis) and percent change in running gait variables. YBT variables include anterior (ANT) reach, posterior-lateral (PL) reach, posterior-medial (PM) reach and composite score (CS). Running variables include peak hip adduction (HAD), peak hip internal rotation (HIR), peak hip abductor moment (Hmom), peak hip abductor impulse (Himp).

Discussion

The purpose of this study was to evaluate the relationship between YBT performance and changes in injury-linked running mechanics at the hip following fatigue. Strength and neuromuscular control of the muscles surrounding the hip are necessary to

both YBT performance and running. Greater strength of the hip musculature has been associated with increased YBT performance,^{68,129} and has also been linked to a reduced risk of developing running injuries.^{31,104} Fatigue has also been shown to increase the prevalence of injury-related running mechanics.^{95,126} These associations led to the hypothesis that YBT performance may predict changes in injury-related running mechanics at the hip following a run to fatigue.

There were no significant differences in the selected running mechanics between the pre and post-fatigue conditions. This was surprising as similar protocols using the Borg RPE scale have reported changes in running mechanics using fatigue protocols of a similar length.^{20,63} However, there were several differences between the protocols of the previously cited studies and this study. The participants in both the Derrick et al. and Koblbauer et al. studies used the same running shoe,^{20,63} whereas our participants were allowed to use their personal running shoes. Several studies have reported that orthoses can cause changes in plantar pressures⁸¹ and joint kinetics⁷² relative to those experienced from a participant's normal footwear. Orthotics are often used to achieve clinically oriented alterations in gait. However, the use of standardized shoes in the Koblbauer et al. and Derrick et al. studies may have significantly altered the participants' running mechanics prior to the fatigue protocols. The burden of running in these conditions may have led the participants in Koblbauer et al. and Derrick et al.'s studies to fatigue quicker, resulting in alterations between the pre and post conditions. Koblbauer et al. also recruited from a novice population that ran fewer than 30 km per week while this study required participants to run at least 20 miles per week.⁶³ Thus, fatigue may have had a

greater influence on running mechanics in the Koblbauer et al. study as participants may not have been as highly conditioned as participants in the current study. The effect sizes in the present study were negligible for the all of the running mechanics variables except for a small to moderate effect on peak hip internal rotation. This suggests that the fatigue protocol may have had an effect on transverse plane hip mechanics, but the sample size was underpowered.

Linear regressions revealed no statistically significant relationships between YBT performance and percent change of any of the running mechanics variables. These results were surprising as both the YBT and running rely on strength and control of the hip musculature. Performing the YBT relies heavily on eccentric movements during each reach, and increased eccentric hip strength may also prevent running injuries.¹⁰⁴ Specifically, higher eccentric strength of the hip abductors in runners has been prospectively linked with a reduced risk of developing patellofemoral pain.¹⁰⁴ While the muscles utilized during the YBT and running may be similar, the way in which the muscles are utilized are very different. The YBT is performed by slowly reaching in each direction as far as possible while maintaining stability. In contrast, running is characterized by the repetitive application and resistance of cyclic loads over short periods of time. The motion of the lower extremities during the stance phase of running and while performing the YBT are highly similar in that they both rely on eccentric strength to resist flexion, adduction and eversion of the hip, knee and ankle. However, running requires the resistance of these forces at impulses much greater than those

experienced during the YBT. Therefore, the YBT may not be applicable to runners because the muscular stressors of running and the YBT are too different.

The objective of the YBT is to reach as far as possible with the non-stance limb, requiring the participant to reach outside the base of support. During running, however, runners typically maintain the lower extremities directly underneath the center of mass (or relatively close) and do not reach outside the base of support. This requirement of the YBT may also be too dissimilar to the movements experienced while running, potentially requiring different levels of strength and endurance of the pelvic and hip musculature. Due to the use of similar muscles the authors hypothesized that the pelvic control required for the YBT would directly translate to pelvic control during running. However, in addition to pelvic control, the YBT also requires much greater ranges of motion of the hip than running. Runners are known to have reduced flexibility, especially in the posterior muscle groups of the lower extremity.¹²⁴ It may be that runners are not used to the ranges of motion required of the YBT. Indeed, YBT scores of multisport populations tend to be much higher than the values in the present study.^{66,107} This suggests that limited flexibility and range of motion may leave the YBT ineffective for running populations.

Running is also a semi-elastic activity that relies partially on musculotendinous elasticity to preserve energy and generate forward propulsion.¹⁰⁸ This is vastly different compared to the YBT, which is performed too slowly to rely on this biological mechanism. While a level of musculotendinous stiffness may be beneficial for running economy, this may also limit the ability to perform the YBT movements. This may also

partially explain the reduced reach distances relative to multisport populations mentioned above. However, the previously cited studies examining YBT performance of multisport populations utilized NCAA Division I athletes, whereas the mean age of participants in this study was 28.75 ± 9.17 years and included participants up to age 44. Given that flexibility generally declines with age it may be that the YBT is more useful in younger, more flexible athletes who can move through the full ranges of motion required of the YBT.² However, this hypothesis should be further investigated.

There were several limitations which need to be considered when interpreting the results of this study. While runners ran in their preferred shoe during the gait analysis the YBT was performed barefoot. Differences in shod versus barefoot YBT performance have yet to be investigated as the YBT is traditionally performed barefoot. However, many prospective studies identifying a relationship between performance on the YBT^{37,46,107} and injury during the following sport season were performed barefoot, indicating the validity of comparing barefoot YBT performance to shod sports. Foot strike pattern was not controlled, and differences in foot strike may have influenced the kinetic variables in this study.¹⁰⁵ The dominant limb, defined as the limb utilized to “kick a ball,” was also selected for this study. While there is some evidence that dynamic postural control is different between dominant and non-dominant limbs,¹⁰² other evidence suggests that it does not differ.⁵⁰ Further, Brown et al. showed that running mechanics did not differ with limb dominance in either a fresh or fatigued state.⁹ The average starting pace for the fatigue protocol in this study was 3.22 ± 0.33 m/s. Many of the runners, however, did not regularly train on a treadmill. Thus, they may have underestimated their

initial self-selected race pace. To adjust for this the runners were allowed to increase their pace as needed.

The relatively small sample size of this study may explain the lack of relationships observed. However, other studies have used similar⁶³ and significantly smaller²⁰ sample sizes to demonstrate fatigue-related changes in running mechanics. Additionally, the runners in this study may have been too highly conditioned for the fatigue protocol to significantly change their running mechanics. The intensity during the fatigue protocol was designed to simulate race conditions, but the runners were conditioned to running for much longer amounts of time than the average time to volitional fatigue observed in this study. Other studies utilizing fatigue protocols of similar times but higher intensities have also observed no changes in running mechanics,¹ suggesting that alterations may be more strongly related to run time rather than intensity in distance runners. Thus, the average length of time running may not have been enough to significantly influence their running mechanics.

Conclusions

This study evaluated the relationship between YBT performance and changes in injury-linked running mechanics at the hip following a run to fatigue. Selected running mechanics at the hip did not change between the pre and post-fatigue conditions. Linear regressions also showed no significant relationship between YBT performance and any of the four running mechanics variables that have been previously linked to injury. This was likely due to the differing neuromuscular demands of the two activities. Both activities require muscular stability of the hip and pelvis. However, running requires the repetitive

resistance of cyclic loads under small ranges of motion, while the YBT requires larger ranges of motion but does not require the resistance of cyclic loads. Thus, the YBT may not be a useful screen to identify changes in injury-linked running mechanics at the hip in distance runners following fatigue. Future research should examine whether YBT performance relates to additional running variables at the knee and ankle that have been linked to injury under fresh or fatigued conditions.

REFERENCES CITED

1. Abt JPS, Tomithy C.; Chu, Yungchien; Lovalekar, Mita; Burdett, Ray G.; Lephart, Scott M. Running kinematics and shock absorption do not change after brief exhaustitve running. *Journal of Strength and Conditioning Research*. 2011;26(6):1479-1485.
2. Adams K, O''Shea P, O'Shea KL. Aging: its effects on strength, power, flexibility, and bone density. *Strength Cond J*. 1999;21(2):65-77.
5. Benis R, Bonato M, La Torre A. Elite Female Basketball Players' Body-Weight Neuromuscular Training and Performance on the Y-Balance Test. *J Athl Train*. 2016;51(9):688-695.
6. Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *JR Stat Soc B*. 1995;57(1):289-300.
9. Brown AM, Zifchock RA, Hillstrom HJ. The effects of limb dominance and fatigue on running biomechanics. *Gait Posture*. 2014;39(3):915-919.
11. Butler RJ, Bullock G, Arnold T, Plisky P, Queen R. Competition-Level Differences on the Lower Quarter Y-Balance Test in Baseball Players. *J Athl Train*. 2016;51(12):997-1002.
13. Chimera NJ, Smith CA, Warren M. Injury history, sex, and performance on the functional movement screen and Y balance test. *J Athl Train*. 2015;50(5):475-485.
18. Davis IS, Bowser BJ, Mullineaux DR. Greater vertical impact loading in female runners with medically diagnosed injuries: a prospective investigation. *Br J Sports Med*. 2016;50(14):887-892.
20. Derrick TR, Dereu D, McLean SP. Impacts and kinematic adjustments during an exhaustive run. *Med Sci Sports Exerc*. 2001;34(6):998-1002.
26. Eskofier BM, Kraus M, Worobets JT, Stefanyshyn DJ, Nigg BM. Pattern classification of kinematic and kinetic running data to distinguish gender, shod/barefoot and injury groups with feature ranking. *Comput Methods Biomech Biomed Engin*. 2012;15(5):467-474.

31. Fredericson M, Cookingham CL, Chaudhari AM, Dowell BC, Oestreich N, Sahrmann SA. Hip Abductor Weakness in Distance Runners with Iliotibial Band Syndrome. *Clinical Journal of Sports Medicine*. 2000;10:169-175.
37. Gonell AC, Romero JAP, Soler LM. Relationship Between The Y Balance Test Scores and Soft Tissue Injury Incidence in a Soccer Team. *International Journal of Sports Physical Therapy*. 2015;10(7):955-966.
40. Gribble PA, Terada M, Beard MQ, et al. Prediction of Lateral Ankle Sprains in Football Players Based on Clinical Tests and Body Mass Index. *Am J Sports Med*. 2016;44(2):460-467.
46. Hartley EM, Hoch MC, Boling MC. Y-balance test performance and BMI are associated with ankle sprain injury in collegiate male athletes. *J Sci Med Sport*. 2018;21(7):676-680.
50. Hoffman M, Schrader J, Applegate T, Koceja D. Unilateral Postural Control of the Functionally Dominant and Nondominant Extremities of Healthy Subjects. *Journal of Athletic Training*. 1998;33(4):319-322.
55. Hreljac A, Marshall R, Hume PA. Evaluation of lower extremity overuse injury potential in runners. *Med Sci Sports Exerc*. 2000;32:1635-1641.
60. Kang MH, Kim GM, Kwon OY, Weon JH, Oh JS, An DH. Relationship Between the Kinematics of the Trunk and Lower Extremity and Performance on the Y-Balance Test. *PM&R*. 2015;7(11):1152-1158.
63. Koblbauer IF, van Schooten KS, Verhagen EA, van Dieen JH. Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. *J Sci Med Sport*. 2014;17(4):419-424.
64. Kristianslund E, Krosshaug T, van den Bogert AJ. Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention. *J Biomech*. 2012;45(4):666-671.
66. Lai WC, Wang D, Chen JB, Vail J, Rugg CM, Hame SL. Lower Quarter Y-Balance Test Scores and Lower Extremity Injury in NCAA Division I Athletes. *Orthop J Sports Med*. 2017;5(8):2325967117723666.

68. Lee DK, Kang MH, Lee TS, Oh JS. Relationships among the Y balance test, Berg Balance Scale, and lower limb strength in middle-aged and older females. *Braz J Phys Ther.* 2015;19(3):227-234.
69. Lee M, Sim S, Jiemin Y. Y-balance test but not functional movement screen scores are associated with peak knee valgus moments during unplanned sidestepping: implications for assessing anterior cruciate ligament injury risk. Paper presented at: International Society of Biomechanics in Sports2017.
71. Leudke LE, Heiderscheit BC, Williams DSB, Rauh MJ. Association of Isometric Strength of Hip and Knee Muscles with Injury Risk in High School Cross Country Runners. *International Journal of Sports Physical Therapy.* 2015;10(6):868-876.
72. Lewinson RT, Worobets JT, Stefanyshyn DJ. Control conditions for footwear insole and orthotic research. *Gait Posture.* 2016;48:99-105.
73. Lewis CL, Foch E, Luko MM, Loverro KL, Khuu A. Differences in Lower Extremity and Trunk Kinematics between Single Leg Squat and Step Down Tasks. *PLoS One.* 2015;10(5):e0126258.
74. Linek P, Booyesen N, Sikora D, Stokes M. Functional movement screen and Y balance tests in adolescent footballers with hip/groin symptoms. *Phys Ther Sport.* 2019;39:99-106.
76. MacMahon JM, Chaudhari AM, Andriacchi TP. Biomechanical injury predictors for marathon runners: striding towards iliotibial band syndrome injury prevention. ISBS; 2000.
79. Maykut JNT-H, Jeffery A.; Paterno, Mark V.; DiCesare, Christopher A.; Ford, Kevin R. Concurrent Validity and Reliability of 2D Kinematic Analysis of Frontal Plane Motion During Running. *International Journal of Sports Physical Therapy.* 2015;10(2):136-146.
81. McCormick CJ, Bonanno DR, Landorf KB. The effect of customized and sham foot orthoses on pantar pressures. *J Foot Ankle Res.* 2013;6(19):1-14.

82. Messier SP, Martin DF, Mihalko SL, et al. A 2-Year Prospective Cohort Study of Overuse Running Injuries: The Runners and Injury Longitudinal Study (TRAILS). *Am J Sports Med.* 2018;46(9):2211-2221.
88. Noehren B, Davis I, Hamill J. ASB clinical biomechanics award winner 2006 prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clin Biomech (Bristol, Avon).* 2007;22(9):951-956.
89. Noehren B, Hamill J, Davis I. Prospective evidence for a hip etiology in patellofemoral pain. *Med Sci Sports Exerc.* 2013;45(6):1120-1124.
91. Noehren B, Schmitz A, Hempel R, Westlake C, Black W. Assessment of strength, flexibility, and running mechanics in men with iliotibial band syndrome. *J Orthop Sports Phys Ther.* 2014;44(3):217-222.
93. Olmsted LC, Carcia CR, Hertel J, Shultz SJ. Efficacy of the Star Excursion Balance Tests in Detecting Reach Deficits in Subjects With Chronic Ankle Instability. *Journal of Athletic Training.* 2002;37(4):501-506.
95. Paquette MR, Melcher DA. Impact of a Long Run on Injury-Related Biomechanics with Relation to Weekly Mileage in Trained Male Runners. *J Appl Biomech.* 2017;33(3):216-221.
100. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star Excursion Balance Test as a Predictor of Lower Extremity Injury in High School Basketball Players. *Journal of Orthopaedic and Sports Physical Therapy.* 2006;36(12):911-919.
102. Promsri A, Haid T, Federolf P. How does lower limb dominance influence postural control movements during single leg stance? *Hum Mov Sci.* 2018;58:165-174.
104. Ramskov D, Barton C, Nielsen RO, Rasmussen S. High eccentric hip abduction strength reduces the risk of developing patellofemoral pain among novice runners initiating a self-structured running program: a 1-year observational study. *J Orthop Sports Phys Ther.* 2015;45(3):153-161.
105. Rice HM, Jamison ST, Davis IS. Footwear matters: influence of footwear and foot strike on load rates during running. *Med Sci Sports Exerc.* 2016;48(12):2462-2468.

107. Smith CA, Chimera NJ, Warren M. Association of y balance test reach asymmetry and injury in division I athletes. *Med Sci Sports Exerc.* 2015;47(1):136-141.
108. Snyder KL, Kram R, Gottschall JS. The role of elastic energy storage and recovery in downhill and uphill running. *J Exp Biol.* 2012;215(Pt 13):2283-2287.
118. Van Gent RN, Siem D, Van Middelkoop M, Van Os AG, Bierma-Zeinstra SM, Koes BW. Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. *Br J Sports Med.* 2007;41(8):469-480; discussion 480.
120. Vitale JA, Torre AL, Banfi G, Bonato M. Effects of an 8-week body-weight neuromuscular training on dynamic balance and vertical jump performances in elite jounior skiing athletes: A randomized controlled trial. *Journal of Strength and Conditioning Research.* 2018;32(4):911-920.
124. Wang SS, Whitney SL, Burdett RG, Janosky JE. Lower extremity muscular flexibility in long distance runners. *JOSPT.* 1993;17(2):102-107.
125. Wen DY. Risk Factors for Overuse Injuries in Runners. *Current Sports Medicine Reports.* 2007;6(5):307-313.
126. Willson JD, Loss JR, Willy RW, Meardon SA. Sex differences in running mechanics and patellofemoral joint kinetics following an exhaustive run. *J Biomech.* 2015;48(15):4155-4159.
129. Wilson BR, Robertson KE, Burnham JM, Yonz MC, Ireland ML, Noehren B. The Relationship Between Hip Strength and the Y Balance Test. *J Sport Rehabil.* 2018;27(5):445-450.
131. Wu G, Siegler S, Allard P, et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion - part I: ankle, hip, and spine. *J Biomech.* 2002;35:543-548.

CHAPTER FIVE

DISCUSSION AND CONCLUSIONS

The YBT is a widely known clinical movement screen used to measure strength, dynamic stability and neuromuscular control in a variety of athletic and clinical populations.^{11,93} The YBT is also used to predict injury risk across a range of sports.^{37,100,107} Strength and neuromuscular control of the muscles surrounding the hip are strong predictors of YBT performance.¹²⁹ These same variables are also essential for running performance^{48,83} and the prevention of injury.^{71,104} Changes in injury-related running mechanics have been shown to occur along the course of a fatiguing run.^{95,126} Thus, the purpose of this thesis was twofold: 1) to evaluate the relationship between YBT performance and running mechanics and 2) to evaluate whether YBT performance can predict changes in injury-linked running mechanics after a run to fatigue. For the remainder of this paper the previous manuscripts will be referred to as Study 1 (A Multivariate Analysis of the Relationships Between Y-Balance Test Performance and Running Mechanics) and Study 2 (The Relationship Between Y-Balance Test Performance and Running Mechanics at the Hip Following Fatigue).

Univariate analysis from Study 1 found no significant relationships between YBT CS and any of the 12 individual running gait variables. However, multivariate analysis identified a strong positive relationship between the two canonical variables, *Balance* and *Mechanics*. The *Balance* variable included all three YBT reach directions while *Mechanics* included the 12 running variables that have been previously linked to injury in runners. The ANT and PL reach directions were positive contributors to *Balance*, while

PM reach was a negative contributor. Further, the PL direction contributed twice as much to the *Balance* canonical variable as ANT. Frontal plane kinetics at the hip and knee were the greatest contributors to the *Mechanics* variable, while the remaining kinematic and kinetic variables exhibited little to no contribution. Integrating these findings suggests that reaching farther in the ANT and PL directions may be associated with lower peak HAb moments and KAb Impulses while running, all other variables held constant. Conversely, a greater PM reach may be associated with lower peak HAb Impulses, all other variables held constant. The vastly different contributions of reach directions emphasize the diversity of neuromuscular control required to perform each reach.⁶⁰ Study 1 also supports the argument that individual reach directions may be more useful than CS in predicting running mechanics. The findings from Study 1 suggest that YBT performance is most closely related to frontal plane kinetics. This makes sense as strength of the hip abductors are predictive of YBT performance.¹²⁹ However, it was interesting that frontal plane kinematics did not have a greater contribution to the *Mechanics* variable given the contribution of frontal plane kinetics.

Study 2 explored the relationships between frontal plane mechanics and the YBT in further detail. Specifically, Study 2 examined whether YBT performance was predictive of changes in frontal plane kinematics and kinetics at the hip following a run to volitional fatigue. Running mechanics did not significantly change between the pre and post fatigue conditions. Univariate analysis also revealed no significant relationships between individual YBT reach directions and percent change in any of the four running mechanics variables. These results suggest that the YBT may not be a useful movement

screen to identify changes in injury-related mechanics at the hip in distance runners following fatigue. This may be partially explained by the different neuromuscular requirements between the YBT and running. While similar muscle groups are used to perform both tasks, the way in which the muscles are utilized are completely different. Performing the YBT requires slow, controlled movements to achieve maximal reach while maintaining stability. Contrarily, running requires the resistance of cyclic loads over short periods of time. Further, running and the YBT have vastly different requirements for flexibility and ranges of motion. Limited flexibility can actually enhance running economy through the elastic storage and return of energy, but may harm YBT performance. The YBT also requires participants to reach far outside their base of support. This is in direct contrast to distance running where the feet generally stay almost directly under the center of mass.

Frontal plane kinetics at the hip were the largest contributors to the correlation between *Balance* and *Mechanics* in Study 1. Therefore, it is reasonable to ask why this relationship was observed in Study 1 but not in Study 2. A CCA condenses two sets of variables onto a single vector, and each vector is then loaded onto its own canonical variable. The CCA maximizes the correlation between the two canonical variables and calculates the weighted contribution of each variable in the vectors to the overall canonical variable. The goal of a CCA is to maximize the correlation between two sets of variables and does not reflect a direct relationship between any of the variables in either set of vectors. A CCA is not a test of statistical significance but an exploratory analysis. Thus, a CCA will weight the input variables in order to maximize the correlation between

two canonical variables, regardless of whether the sub-variables are directly related.

Though the results of Study 1 indicated that frontal plane kinetics at the hip were the greatest contributors to the correlation between the *Balance* and *Mechanics* canonical variables, this does not necessarily reflect a direct relationship between YBT performance and hip mechanics.

Both studies contained several limitations that should be considered. The participants in both studies were free from injury within three months prior to testing. However, we did not otherwise control for injury history. Several studies have shown that previous injury can impair dynamic balance and neuromuscular control,^{52,93} and such deficits may even remain following return to sport.¹¹¹ The studies here also compared barefoot YBT performance to shod running mechanics. While this may appear to be a limitation, many studies have identified relationships between barefoot YBT performance and injury risk in the subsequent sport season.^{37,46,107} This provides evidence for the validity of comparing barefoot YBT performance to shod sports. It should also be noted that running mechanics did not significantly change between the pre and post fatigue conditions in Study 2. Thus, if a relationship between YBT performance and changes in injury-linked running mechanics does exist the runners may not have been fatigued enough to identify this relationship. It may also be difficult to directly compare the results from Studies 1 and 2 because of differences in population. Roughly half of the participants in Study 1 were currently athletes on a Division-I track and field team whereas all participants in Study 2 were from the surrounding community. Even though

participants from both studies met the minimum threshold of 20 mi./week there may be differences in running mechanics between recreational and competitive runners.¹⁵

Results suggest that the YBT may not be useful for predicting the specific running mechanics variables measured here or alterations in those variables in distance runners. However, this may differ between YBT performance metrics. The calculation of a CS can easily camouflage deficiencies in specific muscle groups or ranges of motion, as both differ between reach directions.^{60,92} The results from Study 1 provide evidence for this through the differing contributions of individual reach directions to the *Balance* canonical variable – and in their magnitudes in the relationship between *Balance* and *Mechanics* – and should be further evaluated in running populations. However, these judgements are bound by the conditions and limitations of the two studies, and the YBT may still be useful outside of these conditions. Additionally, these conclusions are based purely on quantitative measurements. Exclusively focusing on the score may not yield sufficient information regarding an individual's running mechanics, even considering individual reach directions. However, this limitation may be mitigated by the expertise of a clinician. The knowledge and experience of physical therapists, athletic trainers and other clinicians allow for a supplementary qualitative evaluation of YBT performance, and may provide great benefit. Further, the YBT may also be used to prospectively establish a baseline for rehabilitation in the case of injury during the sport season.

It is also important to consider the specificity of the YBT, and that development of YBT-specific skill may not directly translate to the improvement of running mechanics. Thus, one could theoretically improve YBT performance without showing

concurrent improvements in injury-related running mechanics. A better solution for quantifying the prevalence of injury-linked running mechanics may be to develop or utilize tests that more directly measure the mechanisms associated with running injuries. However, this is outside the scope of the current thesis and should be further investigated. Both studies here also compared YBT performance in a fresh state to running mechanics, and it has been demonstrated that dynamic balance can change with fatigue.¹¹¹ It may be that YBT performance in a fatigued state is more directly related to injury-linked running mechanics or changes in those mechanics after fatigue, and future studies should evaluate this hypothesis.

The studies here found that YBT CS was not predictive of select injury-related running mechanics in a fresh state in distance runners. There were also no relationships identified between individual reach directions and percent change in running mechanics after a run to volitional fatigue. However, results from Study 1 showed that performance on the individual reach directions contribute differently to the relationship between YBT performance and running mechanics. The discrepancies between Study 1 and Study 2 may be partially explained by slight differences between subpopulations of runners and should be further investigated. Additionally, these relationships may also depend on whether the YBT is performed in a fresh or fatigued state. Until future studies examine these hypotheses, the YBT may still be utilized by clinicians to evaluate deficits in strength and neuromuscular control of particular muscle groups – though, not necessarily in relation to running mechanics – range of motion, and to serve as an additional metric to gauge return to sport readiness.

REFERENCES CITED

11. Butler RJ, Bullock G, Arnold T, Plisky P, Queen R. Competition-Level Differences on the Lower Quarter Y-Balance Test in Baseball Players. *J Athl Train*. 2016;51(12):997-1002.
15. Clermont CA, Osis ST, Phinyomark A, Ferber R. Kinematic Gait Patterns in Competitive and Recreational Runners. *J Appl Biomech*. 2017;33(4):268-276.
37. Gonell AC, Romero JAP, Soler LM. Relationship Between The Y Balance Test Scores and Soft Tissue Injury Incidence in a Soccer Team. *International Journal of Sports Physical Therapy*. 2015;10(7):955-966.
46. Hartley EM, Hoch MC, Boling MC. Y-balance test performance and BMI are associated with ankle sprain injury in collegiate male athletes. *J Sci Med Sport*. 2018;21(7):676-680.
48. Hickson RC, Dvorak BA, Gorostiaga EM, Kurowski TT, C. F. Potential for strength and endurance training to amplify endurance performance. *J Appl Physiol*. 1988;65:2285-2290.
52. Hooper TL, James CR, Brismee JM, et al. Dynamic balance as measured by the Y-Balance Test is reduced in individuals with low back pain: A cross-sectional comparative study. *Phys Ther Sport*. 2016;22:29-34.
60. Kang MH, Kim GM, Kwon OY, Weon JH, Oh JS, An DH. Relationship Between the Kinematics of the Trunk and Lower Extremity and Performance on the Y-Balance Test. *PM&R*. 2015;7(11):1152-1158.
71. Leudke LE, Heiderscheit BC, Williams DSB, Rauh MJ. Association of Isometric Strength of Hip and Knee Muscles with Injury Risk in High School Cross Country Runners. *International Journal of Sports Physical Therapy*. 2015;10(6):868-876.
83. Mikkola J, Rusko H, Nummela A, Pollari T, Hakkinen K. Concurrent endurance and explosive type strength training improves neuromuscular and anaerobic characteristics in young distance runners. *Int J Sports Med*. 2007;28(7):602-611.

92. Norris BT-J, E. Hip- and Thigh-Muscle Activation During the Star Excursion Balance Test. *Journal of Sport Rehabilitation*. 2011;20:428-441.
93. Olmsted LC, Carcia CR, Hertel J, Shultz SJ. Efficacy of the Star Excursion Balance Tests in Detecting Reach Deficits in Subjects With Chronic Ankle Instability. *Journal of Athletic Training*. 2002;37(4):501-506.
95. Paquette MR, Melcher DA. Impact of a Long Run on Injury-Related Biomechanics with Relation to Weekly Mileage in Trained Male Runners. *J Appl Biomech*. 2017;33(3):216-221.
100. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star Excursion Balance Test as a Predictor of Lower Extremity Injury in High School Basketball Players. *Journal of Orthopaedic and Sports Physical Therapy*. 2006;36(12):911-919.
104. Ramskov D, Barton C, Nielsen RO, Rasmussen S. High eccentric hip abduction strength reduces the risk of developing patellofemoral pain among novice runners initiating a self-structured running program: a 1-year observational study. *J Orthop Sports Phys Ther*. 2015;45(3):153-161.
107. Smith CA, Chimera NJ, Warren M. Association of y balance test reach asymmetry and injury in division I athletes. *Med Sci Sports Exerc*. 2015;47(1):136-141.
111. Steib S, Zech A, Hentschke C, Pfeifer K. Fatigue-induced alterations of static and dynamic postural control in athletes with a history of ankle sprain. *J Athl Train*. 2013;48(2):203-208.
126. Willson JD, Loss JR, Willy RW, Meardon SA. Sex differences in running mechanics and patellofemoral joint kinetics following an exhaustive run. *J Biomech*. 2015;48(15):4155-4159.
129. Wilson BR, Robertson KE, Burnham JM, Yonz MC, Ireland ML, Noehren B. The Relationship Between Hip Strength and the Y Balance Test. *J Sport Rehabil*. 2018;27(5):445-450.

CUMULATIVE REFERECES CITED

1. Abt JPS, Tomithy C.; Chu, Yungchien; Lovalekar, Mita; Burdett, Ray G.; Lephart, Scott M. Running kinematics and shock absorption do not change after brief exhaustitve running. *Journal of Strength and Conditioning Research*. 2011;26(6):1479-1485.
2. Adams K, O''Shea P, O'Shea KL. Aging: its effects on strength, power, flexibility, and bone density. *Strength Cond J*. 1999;21(2):65-77.
3. Baker RL, Souza RB, Rauh MJ, Fredericson M, Rosenthal MD. Differences in Knee and Hip Adduction and Hip Muscle Activation in Runners With and Without Iliotibial Band Syndrome. *PM R*. 2018;10(10):1032-1039.
4. Becker J, James S, Wayner R, Osternig L, Chou LS. Biomechanical Factors Associated With Achilles Tendinopathy and Medial Tibial Stress Syndrome in Runners. *Am J Sports Med*. 2017;45(11):2614-2621.
5. Benis R, Bonato M, La Torre A. Elite Female Basketball Players' Body-Weight Neuromuscular Training and Performance on the Y-Balance Test. *J Athl Train*. 2016;51(9):688-695.
6. Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *JR Stat Soc B*. 1995;57(1):289-300.
7. Bomberg E, Birch L, Endenburg N, et al. The Financial Costs, Behaviour and Psychology of Obesity: A One Health Analysis. *J Comp Pathol*. 2017;156(4):310-325.
8. Bredeweg SW, Buist I, Kluitenberg B. Differences in kinetic variables between injured and noninjured novice runners: a prospective cohort study. *J Sci Med Sport*. 2013;16(3):205-210.
9. Brown AM, Zifchock RA, Hillstrom HJ. The effects of limb dominance and fatigue on running biomechanics. *Gait Posture*. 2014;39(3):915-919.
10. Brown AM, Zifchock RA, Hillstrom HJ, Song J, Tucker CA. The effects of fatigue on lower extremity kinematics, kinetics and joint coupling in symptomatic female

runners with iliotibial band syndrome. *Clin Biomech (Bristol, Avon)*. 2016;39:84-90.

11. Butler RJ, Bullock G, Arnold T, Plisky P, Queen R. Competition-Level Differences on the Lower Quarter Y-Balance Test in Baseball Players. *J Athl Train*. 2016;51(12):997-1002.
12. Butler RJ, Southers C, Gorman PP, Kiesel KB, Plisky PJ. Differences in soccer players' dynamic balance across levels of competition. *J Athl Train*. 2012;47(6):616-620.
13. Chimera NJ, Smith CA, Warren M. Injury history, sex, and performance on the functional movement screen and Y balance test. *J Athl Train*. 2015;50(5):475-485.
14. Chimera NJ, Warren M. Use of clinical movement screening tests to predict injury in sport. *World J Orthop*. 2016;7(4):202-217.
15. Clermont CA, Osis ST, Phinyomark A, Ferber R. Kinematic Gait Patterns in Competitive and Recreational Runners. *J Appl Biomech*. 2017;33(4):268-276.
16. Coughlan GF, Fullam K, Delahunt E, Gissane C, Caulfield BM. A comparison between performance on selected directions of the star excursion balance test and the Y balance test. *J Athl Train*. 2012;47(4):366-371.
17. Damiano DLA, Allison S.; Steele, Katherine M.; Delp, Scott L. Can strength training predictably improve gait kinematics? A pilot study on the effects of hip and knee extensor strengthening on lower-extremity alignment in cerebral palsy. *Phys Ther*. 2010;90(2):269-279.
18. Davis IS, Bowser BJ, Mullineaux DR. Greater vertical impact loading in female runners with medically diagnosed injuries: a prospective investigation. *Br J Sports Med*. 2016;50(14):887-892.
19. de la Motte S, Arnold BL, Ross SE. Trunk-rotation differences at maximal reach of the star excursion balance test in participants with chronic ankle instability. *J Athl Train*. 2015;50(4):358-365.

20. Derrick TR, Dereu D, McLean SP. Impacts and kinematic adjustments during an exhaustive run. *Med Sci Sports Exerc.* 2001;34(6):998-1002.
21. Doherty C, Bleakley C, Hertel J, Caulfield B, Ryan J, Delahunt E. Dynamic balance deficits in individuals with chronic ankle instability compared to ankle sprain copers 1 year after a first-time lateral ankle sprain injury. *Knee Surg Sports Traumatol Arthrosc.* 2016;24(4):1086-1095.
22. Dudley RI, Pamukoff DN, Lynn SK, Kersey RD, Noffal GJ. A prospective comparison of lower extremity kinematics and kinetics between injured and non-injured collegiate cross country runners. *Hum Mov Sci.* 2017;52:197-202.
23. Earl JE, Hoch AZ. A proximal strengthening program improves pain, function, and biomechanics in women with patellofemoral pain syndrome. *Am J Sports Med.* 2011;39(1):154-163.
24. Earl JH, Jay. Lower-Extremity Muscle Activation During the Star Excursion Balance Tests. *J Sport Rehabil.* 2001;10:93-104.
25. Engquist KDS, Craig A.; Chimera, Nicole J.; Warren, Meghan. Performance Comparison of Student-Athletes and General College Students on the Functional Movement Screen and the Y Balance Test. *Journal of Strength and Conditioning Research.* 2015;28(8):2296-2303.
26. Eskofier BM, Kraus M, Worobets JT, Stefanyshyn DJ, Nigg BM. Pattern classification of kinematic and kinetic running data to distinguish gender, shod/barefoot and injury groups with feature ranking. *Comput Methods Biomech Biomed Engin.* 2012;15(5):467-474.
27. Farrokhi S, Keyak JH, Powers CM. Individuals with patellofemoral pain exhibit greater patellofemoral joint stress: a finite element analysis study. *Osteoarthritis Cartilage.* 2011;19(3):287-294.
28. Ferber R, Noehren B, Hamill J, Davis IS. Competitive female runners with a history of iliotibial band syndrome demonstrate atypical hip and knee kinematics. *J Orthop Sports Phys Ther.* 2010;40(2):52-58.

29. Filipa A, Byrnes R, Paterno MV, Myer GD, Hewett TE. Neuromuscular training improves performance on the star excursion balance test in young female athletes. *J Orthop Sports Phys Ther.* 2010;40(9):551-558.
30. Frederick EC. Kinematically mediated effects of sport shoe design: a review. *J Sports Sci.* 1986;4(3):169-184.
31. Fredericson M, Cookingham CL, Chaudhari AM, Dowell BC, Oestreich N, Sahrmann SA. Hip Abductor Weakness in Distance Runners with Iliotibial Band Syndrome. *Clinical Journal of Sports Medicine.* 2000;10:169-175.
32. Fregly BJ, Besier TF, Lloyd DG, et al. Grand challenge competition to predict in vivo knee loads. *J Orthop Res.* 2012;30(4):503-513.
33. Fullam K, Caulfield B, Coughlan GF, Delahunt E. Kinematic analysis of selected reach directions of the Star Excursion Balance Test compared with the Y-Balance Test. *J Sport Rehabil.* 2014;23(1):27-35.
34. Gabriner ML, Houston MN, Kirby JL, Hoch MC. Contributing factors to star excursion balance test performance in individuals with chronic ankle instability. *Gait Posture.* 2015;41(4):912-916.
35. Garrison JCB, Jim; Cohen, Kiley; Conway, John. Effects of hip strengthening on early outcomes following anterior cruciate ligament reconstruction. *International Journal of Sports Physical Therapy.* 2014;9(2):157-167.
36. Giandolini M, Gimenez P, Temesi J, et al. Effect of the Fatigue Induced by a 110-km Ultramarathon on Tibial Impact Acceleration and Lower Leg Kinematics. *PLoS One.* 2016;11(3):e0151687.
37. Gonell AC, Romero JAP, Soler LM. Relationship Between The Y Balance Test Scores and Soft Tissue Injury Incidence in a Soccer Team. *International Journal of Sports Physical Therapy.* 2015;10(7):955-966.
38. Gribble PA, Hertel J, Plisky P. Using the Star Excursion Balance Test to assess dynamic postural-control deficits and outcomes in lower extremity injury: a literature and systematic review. *J Athl Train.* 2012;47(3):339-357.

39. Gribble PA, Kelly SE, Refshauge KM, Hiller CE. Interrater reliability of the star excursion balance test. *J Athl Train*. 2013;48(5):621-626.
40. Gribble PA, Terada M, Beard MQ, et al. Prediction of Lateral Ankle Sprains in Football Players Based on Clinical Tests and Body Mass Index. *Am J Sports Med*. 2016;44(2):460-467.
41. Gribble PAH, Jay; Denegar, Craig. R.; Buckley William E. The Effects of Fatigue and Chronic Ankle Instability on Dynamic Postural Control. *Journal of Athletic Training*. 2004;39(4):321-329.
42. Hale SA, Hertel J, Olmsted-Kramer LC. The effect of a 4-week comprehensive rehabilitation program on postural control and lower extremity function in individuals with chronic ankle instability. *J Orthop Sports Phys Ther*. 2007;37(6):303-311.
43. Hall EA, Docherty CL, Simon J, Kingma JJ, Klossner JC. Strength-training protocols to improve deficits in participants with chronic ankle instability: a randomized controlled trial. *J Athl Train*. 2015;50(1):36-44.
44. Hamill J, Miller R, Noehren B, Davis I. A prospective study of iliotibial band strain in runners. *Clin Biomech (Bristol, Avon)*. 2008;23(8):1018-1025.
45. Hannigan JJ, Osternig LR, Chou LS. Sex-Specific Relationships Between Hip Strength and Hip, Pelvis, and Trunk Kinematics in Healthy Runners. *J Appl Biomech*. 2018;34(1):76-81.
46. Hartley EM, Hoch MC, Boling MC. Y-balance test performance and BMI are associated with ankle sprain injury in collegiate male athletes. *J Sci Med Sport*. 2018;21(7):676-680.
47. Hertel JB, Rebecca A.; Hale, Sheri A.; Olmsted-Kramer, Lauren C. Simplifying the Star Excursion Balance Test: Analyses of Subjects With and Without Chronic Ankle Instability. *Journal of Orthopaedic and Sports Physical Therapy*. 2006(36):131-137.

48. Hickson RC, Dvorak BA, Gorostiaga EM, Kurowski TT, C. F. Potential for strength and endurance training to amplify endurance performance. *J Appl Physiol*. 1988;65:2285-2290.
49. Hoch MC, Gaven SL, Weinhandl JT. Kinematic predictors of star excursion balance test performance in individuals with chronic ankle instability. *Clin Biomech (Bristol, Avon)*. 2016;35:37-41.
50. Hoffman M, Schrader J, Applegate T, Kocaja D. Unilateral Postural Control of the Functionally Dominant and Nondominant Extremities of Healthy Subjects. *Journal of Athletic Training*. 1998;33(4):319-322.
51. Hollman JHG, Barbara E.; Kozuchowski, Jakub; Vaughn, Amanda S.; Krause, David A.; Youdas, James W. Relationships Between Knee Valgus, Hip-Muscle Strength, and Hip-Muscle Recruitment During a Single-Limb Step-Down. *Journal of Sport Rehabilitation*. 2009;18(1):104-117.
52. Hooper TL, James CR, Brismee JM, et al. Dynamic balance as measured by the Y-Balance Test is reduced in individuals with low back pain: A cross-sectional comparative study. *Phys Ther Sport*. 2016;22:29-34.
53. Hotta T, Nishiguchi S, Fukutani N, et al. Functional Movement Screen for Predicting Running Injuries in 18-to-24-Year-Old Competitive Male Runners. *Journal of Strength and Conditioning Research*. 2015;29(10):2808-2815.
54. Hreljac A. Impact and Overuse Injuries in Runners. *Medicine & Science in Sports & Exercise*. 2004:845-849.
55. Hreljac A, Marshall R, Hume PA. Evaluation of lower extremity overuse injury potential in runners. *Med Sci Sports Exerc*. 2000;32:1635-1641.
56. Hubbard TJ, Kramer LC, Denegar CR, Hertel J. Contributing factors to chronic ankle instability. *Foot Ankle Int*. 2007;28(3):343-354.
57. Hubbard TJK, Lauren C.; Denegar, Craig R.; Hertel, Jay. Correlations Among Multiple Measures of Functional and Mechanical Instability in Subjects With Chronic Ankle Instability. *Journal of Athletic Training*. 2007;42(3):361-366.

58. Ireland MLW, John D.; Ballantyne, Bryon T.; Davis, Irene M. Hip Strength in Females With and Without Patellofemoral Pain. *Journal of Orthopaedic and Sports Physical Therapy*. 2003;33(11):671-676.
59. Johnston W, Dolan K, Reid N, Coughlan GF, Caulfield B. Investigating the effects of maximal anaerobic fatigue on dynamic postural control using the Y-Balance Test. *J Sci Med Sport*. 2018;21(1):103-108.
60. Kang MH, Kim GM, Kwon OY, Weon JH, Oh JS, An DH. Relationship Between the Kinematics of the Trunk and Lower Extremity and Performance on the Y-Balance Test. *PM&R*. 2015;7(11):1152-1158.
61. Kaya D, Citaker S, Kerimoglu U, et al. Women with patellofemoral pain syndrome have quadriceps femoris volume and strength deficiency. *Knee Surg Sports Traumatol Arthrosc*. 2011;19(2):242-247.
62. Kinzey SJA, Charles W. The Reliability of the Star-Excursion Test in Assessing Dynamic Balance. *Journal of Orthopaedic and Sports Physical Therapy*. 1998;27(5):356-361.
63. Koblbauer IF, van Schooten KS, Verhagen EA, van Dieen JH. Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. *J Sci Med Sport*. 2014;17(4):419-424.
64. Kristianslund E, Krosshaug T, van den Bogert AJ. Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention. *J Biomech*. 2012;45(4):666-671.
65. Kuhman DJ, Paquette MR, Peel SA, Melcher DA. Comparison of ankle kinematics and ground reaction forces between prospectively injured and uninjured collegiate cross country runners. *Hum Mov Sci*. 2016;47:9-15.
66. Lai WC, Wang D, Chen JB, Vail J, Rugg CM, Hame SL. Lower Quarter Y-Balance Test Scores and Lower Extremity Injury in NCAA Division I Athletes. *Orthop J Sports Med*. 2017;5(8):2325967117723666.
67. Lawrence EL, Cesar GM, Bromfield MR, Peterson R, Valero-Cuevas FJ, Sigward SM. Strength, Multijoint Coordination, and Sensorimotor Processing Are

- Independent Contributors to Overall Balance Ability. *Biomed Res Int*. 2015;2015:561243.
68. Lee DK, Kang MH, Lee TS, Oh JS. Relationships among the Y balance test, Berg Balance Scale, and lower limb strength in middle-aged and older females. *Braz J Phys Ther*. 2015;19(3):227-234.
 69. Lee M, Sim S, Jiemin Y. Y-balance test but not functional movement screen scores are associated with peak knee valgus moments during unplanned sidestepping: implications for assessing anterior cruciate ligament injury risk. Paper presented at: International Society of Biomechanics in Sports2017.
 70. Lehr ME, Plisky PJ, Butler RJ, Fink ML, Kiesel KB, Underwood FB. Field-expedient screening and injury risk algorithm categories as predictors of noncontact lower extremity injury. *Scand J Med Sci Sports*. 2013;23(4):e225-232.
 71. Leudke LE, Heiderscheit BC, Williams DSB, Rauh MJ. Association of Isometric Strength of Hip and Knee Muscles with Injury Risk in High School Cross Country Runners. *International Journal of Sports Physical Therapy*. 2015;10(6):868-876.
 72. Lewinson RT, Worobets JT, Stefanyshyn DJ. Control conditions for footwear insole and orthotic research. *Gait Posture*. 2016;48:99-105.
 73. Lewis CL, Foch E, Luko MM, Loverro KL, Khuu A. Differences in Lower Extremity and Trunk Kinematics between Single Leg Squat and Step Down Tasks. *PLoS One*. 2015;10(5):e0126258.
 74. Linek P, Booyesen N, Sikora D, Stokes M. Functional movement screen and Y balance tests in adolescent footballers with hip/groin symptoms. *Phys Ther Sport*. 2019;39:99-106.
 75. Lohse KR, Sherwood DE, Healy AF. How changing the focus of attention affects performance, kinematics, and electromyography in dart throwing. *Hum Mov Sci*. 2010;29(4):542-555.
 76. MacMahon JM, Chaudhari AM, Andriacchi TP. Biomechanical injury predictors for marathon runners: striding towards iliotibial band syndrome injury prevention. ISBS; 2000.

77. Magrum E, Wilder RP. Evaluation of the injured runner. *Clin Sports Med.* 2010;29(3):331-345.
78. Mayer SW, Queen RM, Taylor D, et al. Functional Testing Differences in Anterior Cruciate Ligament Reconstruction Patients Released Versus Not Released to Return to Sport. *Am J Sports Med.* 2015;43(7):1648-1655.
79. Maykut JNT-H, Jeffery A.; Paterno, Mark V.; DiCesare, Christopher A.; Ford, Kevin R. Concurrent Validity and Reliability of 2D Kinematic Analysis of Frontal Plane Motion During Running. *International Journal of Sports Physical Therapy.* 2015;10(2):136-146.
80. McCann RS, Crossett ID, Terada M, Kosik KB, Bolding BA, Gribble PA. Hip strength and star excursion balance test deficits of patients with chronic ankle instability. *J Sci Med Sport.* 2017;20(11):992-996.
81. McCormick CJ, Bonanno DR, Landorf KB. The effect of customized and sham foot orthoses on pantar pressures. *J Foot Ankle Res.* 2013;6(19):1-14.
82. Messier SP, Martin DF, Mihalko SL, et al. A 2-Year Prospective Cohort Study of Overuse Running Injuries: The Runners and Injury Longitudinal Study (TRAILS). *Am J Sports Med.* 2018;46(9):2211-2221.
83. Mikkola J, Rusko H, Nummela A, Pollari T, Hakkinen K. Concurrent endurance and explosive type strength training improves neuromuscular and anaerobic characteristics in young distance runners. *Int J Sports Med.* 2007;28(7):602-611.
84. Milner CE, Ferber R, Pollard CD, Hamill J, Davis IS. Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc.* 2006;38(2):323-328.
85. Moran RW, Schneiders AG, Mason J, Sullivan SJ. Do Functional Movement Screen (FMS) composite scores predict subsequent injury? A systematic review with meta-analysis. *Br J Sports Med.* 2017;51(23):1661-1669.
86. Napier C, MacLean CL, Maurer J, Taunton JE, Hunt MA. Kinetic risk factors of running-related injuries in female recreational runners. *Scand J Med Sci Sports.* 2018;28(10):2164-2172.

87. Neal BS, Barton CJ, Gallie R, O'Halloran P, Morrissey D. Runners with patellofemoral pain have altered biomechanics which targeted interventions can modify: A systematic review and meta-analysis. *Gait Posture*. 2016;45:69-82.
88. Noehren B, Davis I, Hamill J. ASB clinical biomechanics award winner 2006 prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clin Biomech (Bristol, Avon)*. 2007;22(9):951-956.
89. Noehren B, Hamill J, Davis I. Prospective evidence for a hip etiology in patellofemoral pain. *Med Sci Sports Exerc*. 2013;45(6):1120-1124.
90. Noehren B, Pohl MB, Sanchez Z, Cunningham T, Lattermann C. Proximal and distal kinematics in female runners with patellofemoral pain. *Clin Biomech (Bristol, Avon)*. 2012;27(4):366-371.
91. Noehren B, Schmitz A, Hempel R, Westlake C, Black W. Assessment of strength, flexibility, and running mechanics in men with iliotibial band syndrome. *J Orthop Sports Phys Ther*. 2014;44(3):217-222.
92. Norris BT-J, E. Hip- and Thigh-Muscle Activation During the Star Excursion Balance Test. *Journal of Sport Rehabilitation*. 2011;20:428-441.
93. Olmsted LC, Carcia CR, Hertel J, Shultz SJ. Efficacy of the Star Excursion Balance Tests in Detecting Reach Deficits in Subjects With Chronic Ankle Instability. *Journal of Athletic Training*. 2002;37(4):501-506.
94. Olmsted LCC, Christopher R.; Hertel, Jay; Shultz, Sandra J. Efficacy of the Star Excursion Balance Tests in Detecting Reach Deficits in Subjects With Chronic Ankle Instability. *Journal of Athletic Training*. 2002;37(4):501-506.
95. Paquette MR, Melcher DA. Impact of a Long Run on Injury-Related Biomechanics with Relation to Weekly Mileage in Trained Male Runners. *J Appl Biomech*. 2017;33(3):216-221.
96. Payne S, McCabe M, Pulliam J. The Effect of Chronic Ankle Instability (CAI) on Y-Balance Scores in Soccer Athletes. *Journal of Sports Medicine and Allied Health Sciences: Official Journal of the Ohio Athletic Trainers Association*. 2016;2(1).

97. Piva SRG, Edward A.; Childs, John D. Strength Around the Hip and Flexibility of Soft Tissues in Individuals With and Without Patellofemoral Pain Syndrome. *Journal of Orthopaedic and Sports Physical Therapy*. 2005;35(12):793-801.
98. Plisky Pea. Star Excursion Balance Test as a Predictor of Lower Extremity Injury in High School Basketball Players. *Journal of Orthopaedic and Sports Physical Therapy*. 2006;36(12):911-919.
99. Plisky PG, Paul P.; Butler, Robert J.; Kiesel, Kyle B.; Underwood, Frank B.; Elkins, Bryant. The Reliability of an Instrumented Device for Measuring Components of the Star Excursion Balance Test. *North American Journal of Sports Physical Therapy*. 2009;4(2):92-99.
100. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star Excursion Balance Test as a Predictor of Lower Extremity Injury in High School Basketball Players. *Journal of Orthopaedic and Sports Physical Therapy*. 2006;36(12):911-919.
101. Powers CM. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *J Orthop Sports Phys Ther*. 2010;40(2):42-51.
102. Promsri A, Haid T, Federolf P. How does lower limb dominance influence postural control movements during single leg stance? *Hum Mov Sci*. 2018;58:165-174.
103. Radzak KN, Putnam AM, Tamura K, Hetzler RK, Stickley CD. Asymmetry between lower limbs during rested and fatigued state running gait in healthy individuals. *Gait Posture*. 2017;51:268-274.
104. Ramskov D, Barton C, Nielsen RO, Rasmussen S. High eccentric hip abduction strength reduces the risk of developing patellofemoral pain among novice runners initiating a self-structured running program: a 1-year observational study. *J Orthop Sports Phys Ther*. 2015;45(3):153-161.
105. Rice HM, Jamison ST, Davis IS. Footwear matters: influence of footwear and foot strike on load rates during running. *Med Sci Sports Exerc*. 2016;48(12):2462-2468.
106. Schafer DWR, F. L. Exploratory Tools for Summarizing Multivariate Responses. In: Taylor M, ed. *The Statistical Sleuth: A Course in Methods of Data Analysis*. 3rd ed. Boston, MA: Brooks/Cole; 2013:514.

107. Smith CA, Chimera NJ, Warren M. Association of y balance test reach asymmetry and injury in division I athletes. *Med Sci Sports Exerc.* 2015;47(1):136-141.
108. Snyder KL, Kram R, Gottschall JS. The role of elastic energy storage and recovery in downhill and uphill running. *J Exp Biol.* 2012;215(Pt 13):2283-2287.
109. Souza RB, Powers CM. Predictors of hip internal rotation during running: an evaluation of hip strength and femoral structure in women with and without patellofemoral pain. *Am J Sports Med.* 2009;37(3):579-587.
110. Stefanyshyn DJ, Stergiou P, Lun VM, Meeuwisse WH, Worobets JT. Knee angular impulse as a predictor of patellofemoral pain in runners. *Am J Sports Med.* 2006;34(11):1844-1851.
111. Steib S, Zech A, Hentschke C, Pfeifer K. Fatigue-induced alterations of static and dynamic postural control in athletes with a history of ankle sprain. *J Athl Train.* 2013;48(2):203-208.
112. Stiffler MR, Bell DR, Sanfilippo JL, Hetzel SJ, Pickett KA, Heiderscheit BC. Star Excursion Balance Test Anterior Asymmetry Is Associated With Injury Status in Division I Collegiate Athletes. *J Orthop Sports Phys Ther.* 2017;47(5):339-346.
113. Taunton JER, M. B.; Clement, D. B.; McKenzie, D.C.; Lloyd-Smith, D. R.; Zumbo, B. D. A retrospective case-control analysis of 2002 running injuries. *Br J Sports Med.* 2002;36:95-101.
114. Taylor-Haas JA, Hugentobler JA, DiCesare CA, et al. Reduced hip strength is associated with increased hip motion during running in young adult and adolescent male long-distance runners. *IJSPT.* 2014;9(4):456-467.
115. Theisen D, Malisoux L, Gette P, Nührenbörger C, Urhausen A. Footwear and running-related injuries – Running on faith? *Sports Orthopaedics and Traumatology Sport-Orthopädie - Sport-Traumatologie.* 2016;32(2):169-176.
116. Thijs Y, De Clercq D, Roosen P, Witvrouw E. Gait-related intrinsic risk factors for patellofemoral pain in novice recreational runners. *Br J Sports Med.* 2008;42(6):466-471.

117. Thijs Y, Pattyn E, Van Tiggelen D, Rombaut L, Witvrouw E. Is hip muscle weakness a predisposing factor for patellofemoral pain in female novice runners? A prospective study. *Am J Sports Med.* 2011;39(9):1877-1882.
118. Van Gent RN, Siem D, Van Middelkoop M, Van Os AG, Bierma-Zeinstra SM, Koes BW. Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. *Br J Sports Med.* 2007;41(8):469-480; discussion 480.
119. Videbaek S, Bueno AM, Nielsen RO, Rasmussen S. Incidence of Running-Related Injuries Per 1000 h of running in Different Types of Runners: A Systematic Review and Meta-Analysis. *Sports Med.* 2015;45(7):1017-1026.
120. Vitale JA, Torre AL, Banfi G, Bonato M. Effects of an 8-week body-weight neuromuscular training on dynamic balance and vertical jump performances in elite jounior skiing athletes: A randomized controlled trial. *Journal of Strength and Conditioning Research.* 2018;32(4):911-920.
121. Vogler JH, Csiernik AJ, Yorgey MK, Harrison JJ, Games KE. Clinician-Friendly Physical Performance Tests for the Hip, Ankle, and Foot. *J Athl Train.* 2017;52(9):861-862.
122. Walaszek RC, W.; Walaszek, K.; Burdacki, M.; Blaszcuk, J. Evaluation of the accuracy of the postural stability measurement with the Y-Balance Test based on levels of the biomechanical parameters. *Acta of Bioengineering and Biomechanics.* 2017;19(2):121-128.
123. Walter JP, D'Lima DD, Colwell CW, Jr., Fregly BJ. Decreased knee adduction moment does not guarantee decreased medial contact force during gait. *J Orthop Res.* 2010;28(10):1348-1354.
124. Wang SS, Whitney SL, Burdett RG, Janosky JE. Lower extremity muscular flexibility in long distance runners. *JOSPT.* 1993;17(2):102-107.
125. Wen DY. Risk Factors for Overuse Injuries in Runners. *Current Sports Medicine Reports.* 2007;6(5):307-313.

126. Willson JD, Loss JR, Willy RW, Meardon SA. Sex differences in running mechanics and patellofemoral joint kinetics following an exhaustive run. *J Biomech.* 2015;48(15):4155-4159.
127. Willy RW, Davis IS. The effect of a hip-strengthening program on mechanics during running and during a single-leg squat. *J Orthop Sports Phys Ther.* 2011;41(9):625-632.
128. Willy RW, Manal KT, Witvrouw EE, Davis IS. Are mechanics different between male and female runners with patellofemoral pain? *Med Sci Sports Exerc.* 2012;44(11):2165-2171.
129. Wilson BR, Robertson KE, Burnham JM, Yonz MC, Ireland ML, Noehren B. The Relationship Between Hip Strength and the Y Balance Test. *J Sport Rehabil.* 2018;27(5):445-450.
130. Wright AA, Dischiavi SL, Smoliga JM, Taylor JB, Hegedus EJ. Association of Lower Quarter Y-Balance Test with lower extremity injury in NCAA Division 1 athletes: an independent validation study. *Physiotherapy.* 2017;103(2):231-236.
131. Wu G, Siegler S, Allard P, et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion - part I: ankle, hip, and spine. *J Biomech.* 2002;35:543-548.