PERFORMANCE MOTION ANALYSIS UNABLE TO PREDICT RUNNING-RELATED INJURY IN COLLEGIATE ATHLETES

By

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ABSTRACT

The purpose of this study was to determine if a 3D motion capture system's performance motion analysis (PMA) report is capable of identifying factors predictive of running-related injury (RRI) among collegiate distance runners during a cross country season. Thirty-one collegiate cross country runners (17 male, 14 female, mean age = 20.5 ± 1.4 years) gave their consent to participate in the investigation. Subjects were screened in the motion capture system (MCS) and provided with PMA reports assessing their movement quality using several variables (composite score, power, functional strength, dysfunction, vulnerability, and peak knee valgus angle based on measurements of 192 kinetic and kinematic variables). The athletes were then monitored throughout their 13-week competitive season for incidence of RRI. At the end of the season, participants were sorted into injured (n=17) and uninjured (n=14) groups. Injury was defined as appearing on the team injury report as missing or being limited in practice or competition for a week or more in accordance with prior RRI research. Both sexes were also separated into groups based on injury status in accordance with prior RRI research. Independent samples t-tests ($p < 0.05$) revealed no significant findings between groups for any performance variable. The findings identified in this prospective study suggest that the movement screen was unable to identify runners at risk of injury. Future investigations isolating lower extremity movement characteristics in runners may prove more effective at predicting RRI.

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CHAPTER I

INTRODUCTION

STUDY DESIGN

This is a prospective, longitudinal study. Collegiate cross country athletes were screened at the beginning of their season. Per team protocol, injury characteristics of these athletes were tracked throughout the season. The results from motion screenings will be compared to the team injury report to identify predictors of running-related injury.

PURPOSE AND HYPOTHESIS

The purpose of this study is to determine if the Dynamic Athletics Research Institute (DARI) 3D motion capture marker less system's Performance Motion Analysis (PMA) report is capable of predicting incidence of running-related injury (RRI) in athletes during a collegiate cross country season. Data will be used from screenings collected from the University of Kansas' men's and women's cross country teams during the first week of the season and compared to incidence of running-related injury throughout the season. The goal of the researchers is to provide the coaching and sports medicine staff at the university with knowledge to be able to better recognize and address predictors of running-related injury. Previous research using movement screening has indicated college-aged distance runners to be at risk of lower limb injury if they display poor scores on a lower extremity movement screen evaluation (13), and if they have higher levels of knee valgus while running (5). Thus, it is hypothesized that runners suffering from lower extremity RRIs will exhibit poor movement quality indicated by high vulnerability, dysfunction, and knee valgus, and low power, functional strength, and composite scores on the DARI PMA report.

VARIABLES

The DARI PMA report identifies several performance variables after analyzing the 19 foundational movements performed as part of the screening. Included in the report are scores for power, functional strength, dysfunction, and a composite score factoring in each of these parameters which is calculated by adding the strength and power scores and subtracting the dysfunction score. Additionally, "vulnerability" and "exercise readiness" scores are provided in the report. The independent variables observed in this study will include the athlete's performance variables in the DARI motion capture system screening, as detailed on the report.

Since knee adduction and internal rotation while running have been linked to injury in runners (1, 5), peak knee valgus angle during the single-limb squat will be used as an independent variable in order to determine if it is similarly capable.

The dependent variables to be observed in this study include rate and incidence of non-contact running-related injury (RRI). RRI will be defined as any non-contact-induced musculoskeletal trauma that causes an athlete to a week or more of scheduled practice or competition. This definition of RRI is consistent with that of the cross country team's sports medicine staff and that of Buist et al. (2).

LIMITATIONS AND DELIMITATIONS

Due to the structured practice schedule of the team, it was not feasible for athletes to refrain from training on the days of their screenings. Most athletes completed normal training runs prior to their screening sessions. Thus, running-induced fatigue during screening could have influenced results on DARI PMA report scores.

Previous research in the RRI field has indicated prior injury to be a predictive risk factor for future injury (17, 30). However, the research group will not be considering past injury for the study participants, since this information is not available for each individual on the team. The researchers have chosen to limit the subject population to athletes on the 2018 University of Kansas cross country team roster for the duration of the competitive season. In order to be eligible, athletes must have completed the screening requested by the coaches at the beginning of the season and remain on the roster at the end of the season. This population was selected due to the interest of the team's coaching and sports medicine staff in learning more about the causes of running-related injury in their athletes. Furthermore, limiting participants to a single team ensures standardization of training protocol.

ASSUMPTIONS

Given that participants must be members of the 2018 University of Kansas Cross Country team, and that it is not feasible for the researchers to modify the training plan put in place by the coaches, it is assumed that each individual is adhering to similar endurance and resistance training protocol throughout the season.

During the screenings, minimal cues were provided to participants in order to avoid influencing performance. It is assumed that each participant's performance provided an accurate assessment of their natural biomechanical tendencies.

CHAPTER II

REVIEW OF LITERATURE

PREVALENCE OF RUNNING-RELATED INJURIES

Overuse injury ails athletes who participate in endurance activities as a sport, and distance running is no exception. Researchers report lower extremity injury rate in habitual runners ranges from 19.4% to 79.3% yearly (17, 30). In a more experienced population of competitive track and field athletes, Jacobsson et al. reported a rate of 36.9% to 49.0% yearly (14). In the lower extremities, the knee is most commonly injured at a rate of 7.2% to 50% of incidents, followed by the lower leg at 9.0% to 32.2% and the foot at 5.7% to 39.3% (30). These injuries affect all structural components of the lower extremities, including bones, muscles, and joints (17, 22, 30). It important for athletes and their support groups to be able to identify and correct any modifiable factors contributing to increased risk of running-related injury.

FACTORS CONTRIBUTING TO RUNNING-RELATED INJURY

Running-related injuries are caused by a variety of contributing factors and thus it can be difficult to determine a single most important factor when determining injury risk. A handful of factors related to injury will be discussed in this section.

Excessive training volume has been linked to increased injury rates in runners (6, 7, 17, 31). Macera et al. indicated a weekly running volume of greater than 64 kilometers (approximately 40 miles) per week as a significant risk factor for injury in habitual runners (17). Walter et al. reported similar findings in a prospective study tracking 180 runners over 12 months (31). According to these two studies, collegiate running may inherently place athletes at a higher risk for injury, given that collegiate distance running programs typically exceed training volumes of 64 kilometers on a consistent basis (4). Furthermore, it is common for collegiate distance runners to train year-round without a significant break, another habit reported to increase risk of running-related injury (31). Excessive training volume is likely a factor in several running-related injuries, and it can lead to or result in other comorbidities placing an athlete at an even greater risk of injury.

When an athlete trains at chronic volumes that are higher than his or her body can adapt to, physiological signs can indicate risk of injury. Bone mineral density (BMD), as measured by dual energy x-ray absorptiometry (DXA) scanning, is a common method of assessing an athlete's risk of bone injury (10). Goolsby and colleagues reported low BMD to be associated with an increased risk of stress injury in athletes. Furthermore, the researchers concluded that when recovering from stress fractures, low BMD groups experienced slower healing times than high BMD groups.

Iron deficiency is commonly associated with low energy availability and suppressed immune function, and can compromise bone health (24, 29). Characteristics of iron deficiency include suppressed growth hormone secretion, bone breakdown, and impaired thyroid function (24). These events contribute to a weakened skeletal system, placing athletic individuals at a greater risk of bone injury.

The Macera group indicated previous injury to be a risk factor for RRI (17). When tracked prospectively for twelve months, runners who suffered an injury within the year leading up to the study were significantly more likely to suffer another injury than subjects who were injury-free in the prior year. There are a handful of possible explanations for this occurrence including failure to address and correct mechanisms which led to injury, acquisition of poor movement patterns in order to compensate for injury-related pain, or insufficient recovery to allow for full healing of the injury.

Whether or not sex plays a role in injury risk is a point of contention in research. While some groups have claimed injury risk to be independent of sex (26, 31), others have reported greater risk between sexes when certain types of injuries are considered. For example, Satterthwaite et al. suggest males may be at a greater risk for hamstring and calf injury, and females may exhibit increased risk for hip injuries (27). Researchers should aim to separate key variables such as injury location or biomechanical characteristics in order to identify the differences in RRI risk between sexes.

Body mass index (BMI, measured in kg/m^2), may serve as an indicator of RRI risk. Marti et al. reported a BMI of <19.5 to be a risk factor for injury in male runners (18) while Buist et al. reported higher BMI to be related to injury in female runners (2).

Other factors reported to contribute to an increased risk of RRI include being a competitive runner (31), shoe age of greater than 6 months (28), and running on harder surfaces (17). A sample taken of collegiate runners contains individuals displaying one or more of these attributes.

BIIOMECHANICAL PREDICTORS OF RUNNING-RELATED INJURIES

In addition to the risk factors previously discussed, several studies have addressed the relationship between biomechanical characteristics and injury. This section will explore the kinetic and kinematic variables that may play a role in running-related injuries.

The lower back, hips, knees, and lower extremities are all subject to significant stress while running, and are commonly involved in RRIs. Inefficient running mechanics can lead to abnormal lower extremity alignment, or vice-versa. By nature, running is a highly repetitive activity and thus flawed movement patterns can place high loads of stress on areas not equipped to handle such loads. If mechanical issues are left unaddressed, they may lead to recurring injury.

As mentioned above, past injury has been indicated as a predictor for running-related injury (17). Thus, injury history of the runner is an important consideration when assessing RRI risk. It is essential for coaches, trainers, and medical professionals to do their best to identify and correct any mechanical flaws with an injured individual’s gait in order to prevent chronic injury.

Research cites a handful of biomechanical characteristics as culprits for running-related injuries. There is evidence pointing to abnormal hip kinematics as a culprit for running-related injury. Research links hip adduction to common RRIs, including tibial stress fractures (25) and iliotibial band syndrome (22).

In addition to the hip, kinetic and kinematic analysis of the knee is common in RRI research. In 2006, Milner et al. reported knee stiffness and increased vertical loading rate while running to be associated with an increased risk of tibial stress fractures (19). In 2015, Aderem et al. published a systematic review that indicated knee internal rotation (KIR) moment as a predictor for iliotibial band syndrome in runners (1). More recently, a prospective study performed by Dudley et al. indicated greater knee adduction moment (KAM) as a significant predictor of RRI in collegiate runners, suggesting weakness of hip abductor musculature leading to the inability to control excessive adduction in the kinetic chain (5).

The numerous potential causes of running-related injury illustrate the complex and multifactorial nature of its onset. In order to prevent RRI it is important to identify and correct as many risk factors as possible. Coaches and healthcare professionals face the challenge of assigning training loads sufficient to stimulate adaptations while avoiding incidence of injury. Many of the factors related to injury such as training volume and load can be controlled, while some, such as anatomical factors and sex, cannot be. All of these factors should be taken into consideration when designing a training plan. A tool capable of screening for sub-optimal biomechanical patterns would be of great value to runners, coaches, and sports medicine professionals. The emerging research to be discussed below may serve as an effective means of movement screening for runners.

MOVEMENT SCREENING FOR ATHLETES

Injury in sport can lead to reduced training capacity and may force the athlete to miss practice or competition. A reliable screening tool capable of predicting injury would be of value to a team's coaches and medical personnel. Effective screening would give the athlete the chance to address and correct movement inefficiencies before they result in injury.

One tool that has been used to screen runners is the Functional Movement Screen (FMS) technique from Cook et al. (3). The FMS consists of seven tasks reported to be fundamental to human movement. Each task is performed by the subject, and then scored the observer according to a standardized rubric. Scores and can be used to determine an athlete's movement quality. Each task is given a score on a 4-point scale for each movement, with a score of 21 being the best possible combined score. For each task, a score of 3 indicates perfect form, a score of 2 reflects task completion with compensation, a score of 1 means completion of the task improperly, and a score of 0 indicates pain while attempting the task (3). Theoretically, results of the FMS can equip a team's coaches, trainers, and medical personnel with the ability to address and correct any movement inefficiencies in their athletes. The FMS has been shown to be effective at screening for injury in sports such as American football (15), and also in training of prospective Marine Corps officers (16). The success of the FMS shows that movement screening can be a viable option for assessing risk of athletic injury.

MOVEMENT SCREENING FOR DISTANCE RUNNERS

Running is highly repetitive in nature. Distance runners perform the same movement thousands of times during a single session. Unhealthy movement patterns denoted by poor hip and knee control as mentioned above can pose a significant threat to the athlete's running health. Research points to the viability of neuromuscular training programs as a means to change inefficient or poor movement patterns in athletes (11, 12). A screening system capable of identifying biomechanical risk factors in runners would allow these individuals, as well as coaches and sports medicine professionals, to address and fix the mechanisms placing them at higher risk of RRI.

Recent studies have attempted to use screening systems as tools to predict running-related injury. Despite its effectiveness in some sports and in predicting injury amongst Marine Corps trainees running a 3-mile endurance test (15, 16), the FMS mentioned in the previous section has been shown to be a poor predictor of running-related injury in competitive distance runners (23). The Padilla study reported higher FMS scores to be related to a higher risk of injury in collegiate-level runners. These findings are counter-intuitive since greater FMS scores are intended to reflect higher movement pattern quality, which theoretically indicates lower risk of injury.

Running is a task largely composed of lower extremity and trunk mechanics, and taking into account upper extremity mechanics might skew results of the FMS score in terms of its ability to predict injury in the distance runner population. Many of the biomechanical risk factors mentioned above can be attributed to lower extremity inefficiencies such as poor hip and knee control. These movement patterns are likely not heavily influenced by the upper extremities, and thus the FMS whole-body screening approach may lack sensitivity when screening for running injury. The research done by Hotta et al. reports evidence in line with this suggestion (13). The Hotta group looked at FMS scores of eighty-four 18- to 24- year old competitive runners, and were unable to find evidence of the ability of composite FMS score to predict injury in the group of runners. However, the group's findings were different when the composite score was broken down by task. The researchers were able to report a significant difference in performance on the deep squat (DS) and active straight leg raise (ASLR) FMS tasks between the injured and non-injured groups. The group concluded that DS and ASLR may be useful screening tools for risk of RRI. These findings suggest that movement screening systems aimed at predicting RRI may be more effective if they place an emphasis on assessment of lower extremity mechanics.

DARI MOTION CAPTURE SYSTEM SCREENING

The DARI Motion Capture System (Overland Park, KS) is a 3-D motion capture system (MCS) used to analyze movement performance variables. The system is marker-less, which means it does not require the subject being screened to place tracking markers on anatomical landmarks in order for the system's cameras to track human joint segments.

After a subject is screened in the system, DARI analyzes kinetic and kinematic variables to provide a Performance Motion Analysis (PMA) report. The PMA report provides an assessment of the subject's muscular power, functional strength, and dysfunction. This assessment suggests areas that the athlete may need to address in order to achieve optimal movement. The DARI report provides an overall composite score, which combines the three aforementioned parameters and is intended to reflect an individual's "exercise readiness." The report offers a "vulnerability" measurement, which takes into consideration all of the tasks performed by the subject, and reports vulnerability to injury in terms of a percentage value.

Finally, the report offers measurements of joint torque and angle during several of the tasks performed.

The DARI motion capture system can serve as a valuable tool for risk assessment in athletes. MCS have been shown to produce valid measurements of force production (9). Additionally, a test-retest reliability study performed by Mosier et al. showed several DARI performance measures to have excellent reliability with intraclass correlation coefficients of greater than 0.8 across four visits (20).

Recently, Mosier et al. conducted research examining the DARI system's ability to serve as an injury-risk screening system for NCAA Division I football players. "At-risk" individuals were identified based off of the DARI report's measures of vulnerability, composite score, strength-power discrepancy, and joint torque differences (21). The group identified five "at-risk" individuals. Three of these individuals went on to suffer season-ending non-contact injuries. Furthermore, none of the 68 players screened by the system were classified as "not at risk" and went on to experience an injury of such nature. The findings of the Mosier study suggest the DARI PMA report may be a valid tool for injury-risk assessment in football players, yet further investigation is required to determine the tool's effectiveness for other athletic activities.

USING SCREENING INFORMATION TO TARGET RISK FACTORS

After identifying a biomechanical risk factor in a runner, the next step in injury prevention is to correct the movement inefficiency. Previous research has indicated the ability of runners to correct many modifiable movement patterns. For example, Edwards et al. showed that runners were able to successfully decrease their stride length and consequentially their probability of a stress fracture due to decreased strain magnitude at foot strike (6). Similarly, Heiderscheit et al. reported lower magnitudes of force absorbed at the hip and knee during running when athletes simply increased their step rate (11). Decreasing the force absorbed at the hip and knee even by small amounts is of value to runners, since these are common sites of overuse injury. Another study performed by Fredericson et al. showed that runners diagnosed with iliotibial band syndrome were able to overcome their symptoms after participating in a 6-week hip abductor strengthening program (8). Not only did 22 of the 24 runners overcome their symptoms, they also reported no recurrence of symptoms after a follow-up survey conducted six months after the program (8). These findings illustrate the capability of runners to address and correct biomechanical risk factors once they are properly identified.

In the Edwards and Heiderscheit studies, runners successfully decreased their stride lengths in the former and increased their step rates in the latter, while in the Fredericson study, the athletes were able to improve hip abductor strength. In these studies, the runners were informed about the risk factors they exhibited, and were able to implement strategies to reduce risk. An MCS such as the DARI could hold value as a screening tool capable of identifying risk factors in order for runners to be able implement risk-reducing strategies.

CONCLUSION

Running related injury is a common occurrence in habitual runners. Collegiate distance runners may be at an even greater risk of RRI due to the high intensity and volume demanded by their training programs (17, 31). Several factors contribute to injury in runners, many of which are modifiable kinetic and kinematic characteristics (1, 5). Previous research has attempted to identify these risk factors using the Functional Movement Screen (3) in order for athletes to be able to correct movement inefficiencies (13, 23). However, there is a lack of a valid and reliable movement screening system capable of predicting RRI. The DARI 3-D motion capture system has not been tested in a population of runners, and it may be capable of equipping runners and their support groups with the knowledge necessary to identify and correct movement inefficiencies linked to running-related injury.

CHAPTER III

MANUSCRIPT FOR INTERNATIONAL JOURNAL OF EXERCISE SCIENCE

Performance Motion Analysis Unable to Predict Running-Related Injury in Collegiate Distance Runners

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ABSTRACT

The purpose of this study was to determine if a 3D motion capture system's performance motion analysis (PMA) report is capable of identifying factors predictive of running-related injury (RRI) among collegiate distance runners during a cross country season. Thirty-one collegiate cross country runners (17 male, 14 female, mean age = 20.5 ± 1.4 years) gave their consent to participate in the investigation. Subjects were screened in the motion capture system and provided with PMA reports assessing their movement quality using several variables (composite score, power, strength, dysfunction, and vulnerability, based on measurements of 192 kinetic and kinematic variables). The athletes were then monitored throughout their 13-week competitive season for incidence of RRI. At the end of the season, participants were sorted into injured (n=17) and uninjured (n=14) groups. Injury was defined as appearing on the team injury report as missing or being limited in practice or competition for a week or more, in accordance with prior RRI research. Each sex was also separated into groups based on injury status. Independent samples t-tests ($p<0.05$) revealed no significant findings between groups for any performance variable. The findings identified in this prospective study suggest that the movement screen was unable to identify runners at risk of injury. Future investigations isolating lower extremity movement characteristics in runners may prove more effective at predicting RRI.

KEY WORDS: movement screen, motion capture, cross country

INTRODUCTION

Running-related injury (RRI) is a common occurrence among distance runners. Researchers report that lower extremity injury rate in habitual runners ranges from 19.4% to 79.3% yearly (7, 30, 32). In the lower extremities, the knee is most commonly injured -- reportedly at a rate of 7.2% to 50% of incidents for runners -- followed by the lower leg at 9.0% to 32.2% and the foot at 5.7% to 39.3% (30). It is important for these athletes and their support groups to be able to identify and correct modifiable factors contributing to increased risk of injury.

Variables attributed to increased risk of RRI include poor nutrition habits (10, 24, 29), excessive training volume, history of past injury (17), and lower extremity biomechanical characteristics of the athlete such as knee internal rotation during running (1, 5, 19, 22, 25). Several of these factors are modifiable and can be addressed and corrected with the proper strategies. For example, Fredericson et al. demonstrated a reduction in iliotibial band syndrome symptoms after a hip abductor strengthening program (8). Similarly, Heiderscheit et al. reported lower magnitudes of force absorbed at the hip and knee during running when athletes simply increased their step rate (11). These studies illustrate the capability of runners to reduce likelihood of injury when equipped with proper strategies.

A valid and reliable method of assessment is required in order to properly address injury risk factors. The Functional Movement Screen™ (FMS) (3) has been used for this purpose. The FMS is a standardized testing system scoring individuals on performance in seven tasks fundamental to human movement. These tests include deep squat, hurdles step, in-line lunge, active straight leg raise, shoulder mobility, rotary stability, and a trunk stability push-up. The FMS has been shown to be capable of identifying injury risk in athletic populations of football players and military officers (15, 16).

The FMS composite score has not been a reliable screening tool for identifying injury risk factors in running populations (13, 23). Collegiate runners, along with their coaches and sports medicine staff, could benefit from a movement screening system that allow them to identify characteristics contributing to greater likelihood of injury.

Three-dimensional motion capture systems (MCS) may be of use in RRI screening. These systems can be used to analyze movement performance variables. A markerless system does not require the subject to place tracking markers on anatomical landmarks in order for the system's cameras to locate human joint segments. The 3D MCS used in this investigation analyzes kinetic and kinematic variables to provide a Performance Motion Analysis (PMA) report. The PMA report provides an assessment of the subject's muscular power, functional strength, and dysfunction. The resulting report provides an overall composite score, a measure of the athlete's overall performance in the screening. Finally, the report also offers a 'vulnerability' measurement, intended to reflect an individual's susceptibility to injury. Scores from the PMA report do not have specific units. Rather, each score is composed of aggregate calculations from variables associated with each task performed by the subject. Each performance assessment variable is influenced more heavily by certain sets of tasks. Power scores are derived mostly from performance variables associated with jump tasks, while single- and double-limb squat characteristics weigh heavily for functional strength, and imbalances and asymmetries throughout the screening compose the dysfunction scores. Additionally, the PMA normalizes strength and power scores in order to place them on the same scale and allow for direct comparisons. The overall composite score reported by the PMA is calculated by subtracting the dysfunction score from the sum of the strength and power scores. The PMA aggregates vulnerability score based on the individual's scores in relation to normative data sets. This measure is reported in terms of a percentage is intended to reflect the likelihood that an individual experiences a non-contact soft tissue injury.

The MCS can be a valuable tool for risk assessment in athletes. Recently, Mosier et al. conducted research examining the ability of the MCS to serve as an injury risk screening system for NCAA Division I football players (21). Out of the sample of 68 athletes screened, the group identified five 'at-risk' individuals based on PMA scores. Three of the five "at-risk" individuals later suffered season-ending non-contact injuries, while zero of the 63 "not at-risk" individuals suffered season-ending non-contact injuries. The findings of the Mosier study suggest the PMA report from an MCS may be a valid tool for injury-risk assessment in football players.

Research using the 3-D markerless MCS to assess injury risk is still in its early stages. Injury is a common occurrence among collegiate distance runners and there is a lack of a valid injury screening tool for these athletes. Since previous research suggests that movement screening can be used to identify injury risk factors in athletic populations, the purpose of this investigation was to determine if a 3D MCS PMA could identify factors predictive of running-related injury among collegiate distance runners. The researchers hypothesized that the performance variables of power, functional strength, and composite score would be lower in the injured group, and that dysfunction, vulnerability, and peak knee valgus would be higher.

METHODS

Participants

A total of 31 healthy collegiate distance runners (14 female, 17 male, mean age = 20.5 ± 1.4 years) participated in this study. In order to be eligible on their National Collegiate Athletics Association (NCAA) Division I cross country team, athletes were subject to routine physicals conducted by the sports medicine staff. These physicals are a requirement for all student-athletes at the school and were not unique to participants. Prior to enrollment each participant performed a Dynamic Athletics Research Institute Motion Capture System (Overland Park, KS) screening, which was requested by their coaches and medical personnel. Participants signed a consent form approved by the University Institutional Review Board allowing the investigators to use their screening results and medical information appearing on the team injury report for the 2018 NCAA cross country season. The pre-season motion screening and signed consent form were required for participation in the study.

Protocol

Screenings using a markerless MCS took place during the first week of practice of the 2018 NCAA cross country season. The principle investigator administered every screening in order to prevent variability amongst test administrators. Standardized minimal cues were given to limit influence on natural performance in the screening. After each screening, a PMA report was generated using the MCS program software. The PMA report evaluates 192 kinetic and kinematic variables based upon performance in 19 functional movements common in sport, providing an assessment of the athlete's strengths and weaknesses. These variables are reported in composite measures of power, functional strength, dysfunction, exercise readiness, and vulnerability. The PMA report does not give specific units in its assessment of performance.

The study followed a prospective longitudinal design. Per team protocol, incidence of RRI amongst the participating athletes was tracked throughout the 13-week season on an injury report. RRI was defined as any non-contact induced lower limb musculoskeletal injury that limited or prevented participation in team activity for 7 or more days. This definition is in line with prior research conducted by Buist and colleagues (2). Information taken from the report included injury type and location, and time of limitation in days.

Statistical Analysis

Once PMA and injury report data was compiled, individuals were sorted into "injured" (experiencing at least one RRI) and "uninjured" (experiencing no RRIs) groups. Statistical analysis was performed using IBM SPSS Statistics (Version 25). Mixed-factorial ANOVAs were conducted to examine the interactions between groups. Independent samples t-tests ($p<0.05$) were used to compare the mean difference between "injured" and "uninjured" groups, between sexes, and within sex based on injury status for PMA variables (composite, power, strength, dysfunction, vulnerability, and peak knee valgus scores).

Improper nutrition may play a large role in occurrence of bone stress injuries (10). In order to minimize influence of nutrition, a separate analysis removed individuals experiencing bone injuries during the season from the subject population and used the same test procedure as above.

RESULTS

Recorded data

The data displayed in **Table 1** summarizes subject characteristics.

Table 1: Participant demographics **(**$\bar{X}$±SD)

Group	Body weight (kg)	Height (m)
Subject group (n=31)	61.4 ± 4.98	1.76 ± .068
Males (n=17)	64.0 ± 4.01	1.81 ± .046
Females (n=14)	58.2 ± 4.44	1.71 ± .048

The data displayed in **Table 2** represents the variables taken from the PMA reports generated from the MCS screenings that were explained in the introduction. The data is expressed in mean ± standard deviation format.

Table 2: Performance Motion Analysis variable comparisons ($\bar{X}$±SD)

Group	MCS composite score	Power	Functional Strength	Dysfunction	Vulnerability (%)	Peak Knee Valgus (˚)
Sample group (n=31)	1450 ± 196	812 ± 124	751 ± 138	105 ± 43.1	41.0 ± 9.90	4.61 ± 2.08
Injured (n=14)	1430 ± 138	792 ± 133	741 ± 131	104 ± 55.0	42.7 ± 12.4	4.13 ± 1.97
Uninjured (n=17)	1480 ± 240	828 ± 121	760 ± 151	106 ± 33.9	39.6 ± 7.8	5.01 ± 2.14
Males (n=17)	1500 ± 211	880 ± 117*	734 ± 129	109 ± 51.2	42.2 ± 11.4	4.11 ± 2.27
Females (n=14)	1400 ± 175	729 ± 80.4	772 ± 156	100 ± 34.1	39.5 ± 8.4	4.84 ± 1.94
Injured males (n=7)	1480 ± 167	887 ± 93.2	712 ± 142	117 ± 72.3	45.6 ± 14.8	3.39 ± 2.16
Uninjured males (n=10)	1520 ± 244	875 ± 137	749 ± 134	104 ± 33.0	39.9 ± 8.4	4.62 ± 2.32
Injured females (n=7)	1380 ± 80.0	696 ± 93.3	769 ± 123	91.0 ± 30.1	39.9 ± 10.0	4.87 ± 1.58
Uninjured females (n=7)	1430 ± 41.0	762 ± 52.3	775 ± 194	110 ± 37.5	39.1 ± 7.4	4.80 ± 2.37

*significant at p<.01

A total of 24 incidences of non-contact running-related injury appeared on the team's injury report during the 13-week competitive season. Of the 24 total injuries reported, 16 led to a week or more of missed and/or limited participation. A total of 14 of the 31 (45.1%) athletes screened experienced the 16 limiting injuries. There were 3 season-ending injuries, each attributed to bone stress fractures. **Table 3** shows the 16 injuries that led to a week or more of missed time on the team injury report.

Table 3. Injuries that led to a week or more of missed time during the competitive season

Injury Type	**Body Site**
Tenosynovitis	Achilles Tendon
Nerve Involvement	Iliopsoas
Bursitis	Infrapatellar Bursa
Strain	Soleus
Tendinosis	Peroneals
Stress Reaction	Navicular
Stress Reaction	Tibial Shaft
Sprain	Talonavicular Joint
Stress Reaction	Tibial Shaft
Soreness	Sacrum
Tenosynovitis	Achilles Tendon
Soreness	3rd Metatarsal
Tendinitis	Iliopsoas
Impingement	Infrapatellar Bursa
Pain	General Hip
Sprain	Anterior Talofibular Ligament

Comparison between groups

At a significance level of $\alpha = 0.05$, mixed factorial ANOVAs revealed no significant two-way interaction between injury status and sex for composite score ($p = 0.919$), power ($p = 0.306$), functional strength ($p = 0.773$), dysfunction ($p = 0.326$), vulnerability ($p = 0.514$), or peak knee valgus angle ($p = 0.722$). There was no main effect for injury status for composite score ($p = 0.537$), power ($p = 0.481$), functional strength ($p = 0.695$), dysfunction ($p = 0.870$), vulnerability ($p = 0.402$), or peak knee valgus angle ($p = 0.203$). There was no main effect for sex for composite score ($p = 0.185$), functional strength ($p = 0.442$), dysfunction ($p = 0.536$), vulnerability ($p = 0.396$), or peak knee valgus angle ($p = 0.112$). The only main effect observed was for power between sexes ($p<0.000$).

Independent samples t-tests revealed no significant difference between injured (n=14) and uninjured (n=17) groups for MCS composite score ($p = 0.463$), power ($p = 0.429$), functional strength (p = 0.718), dysfunction (p = 0.894), vulnerability (p = 0.401), or peak knee valgus angle (p = 0.246).

Independent samples t-tests between injured females (n=7) and uninjured females (n=7) revealed no significant difference between groups for composite score (p = 0.596), power (p = 0.127), functional strength (p = 0.950), dysfunction (p = 0.313), or vulnerability (p = 0.882), or peak knee valgus angle (p = 0.948). The same analysis for injured (n=7) and uninjured males (n=10) revealed no significant difference between groups for composite score (p = 0.726), power (p = 0.838), functional strength (p = 0.582), dysfunction (p = 0.652), vulnerability (p = 0.328), or peak knee valgus angle (p = 0.285).

In a separate analysis between individuals with injuries not described as "bone-related" (n=11) and uninjured individuals (n=17) independent samples t-tests revealed no significant difference between groups for composite score (p = 0.480), power (p = 0.595), functional strength (p = 0.666), dysfunction (p = 0.704), vulnerability (p = 0.285), or peak knee valgus angle (p = 0.490).

DISCUSSION

The purpose of this study was to determine if the 3D MCS PMA report is capable of identifying factors predictive of running-related injury among collegiate distance runners during a collegiate cross country season. It was hypothesized that individuals affected by running-related injuries will exhibit poor movement quality scores on a 3-D motion screening assessment.

No significant findings were observed between any of the groups used in the statistical analysis. The inconclusive findings suggest that the movement screen lacks validity when screening for injury factors in these collegiate runners. It should be noted that the composite scores observed in this investigation are similar to those seen in unpublished normative data on NCAA Division I cross country athletes held by Fry et al.

Although the 3D MCS movement assessment was not shown to be effective in the present study, data from our laboratory has shown the system to be capable of identifying athletes at risk of injury (21). These athletes were collegiate football players. Since the screening system reports its scores based off short bouts of activity (i.e. “single-leg hop,” and “depth-jump”) its performance ratings may be better suited for assessment of risk in activities more similar in nature. Football is a sport consisting of several brief, explosive movements that demand high amounts of power and strength, which could explain the effectiveness of the system as a risk-screening tool in prior observations. Distance running, on the other hand, is a task that requires greater volume of work, relying more heavily on muscular endurance and less on maximal power and strength. This could explain the lack of findings in the present context.

The 3-D motion capture system reports its scores based on performances in all 19 movements it records. Some of these tasks involve only lower limb movement (i.e. “lunge,” and “squat”), however some call solely for upper limb movement (i.e. “shoulder abduction,” and “shoulder flexion”). Thus, performance measurements integrate full body biomechanical characteristics in the final score report. Previous research has shown that a full body movement screen may not be effective in assessing injury risk for runners (13, 23). However, researchers have found lower limb sub scores of the same movement screen to be more effective indicators of injury risk for runners (13). Keeping these findings in mind, it is reasonable to suggest that a performance report based on scores from only lower limb movements might yield more significant results.

Knee adduction and internal rotation while running have been linked to running-related injury (1, 5). In addition to measures of athletic performance, the MCS assessment also reports biomechanical variables such as joint angle and torque measurements for several of the tasks performed. Although the system's screenings are not capable of screening running gait, the researchers wanted to determine if knee valgus during a single-limb squat task could similarly predict injury. A runner exhibiting high valgus in this task may be at a higher risk of RRI, and could reduce risk of injury by using corrective exercises to address the flawed movement pattern. However, based on the current results, the researchers were unable to distinguish a significant relationship between occurrence of injury and peak knee valgus during the single-limb squat.

One of the limitations to this investigation was the relatively low sample size. The sample of 31 individuals from the same team was chosen in order to control for factors including training volume, intensity, equipment, and terrain, all reported to be important in determining injury risk among runners (17, 30). Although important to control for these factors, the tradeoff of a small sample may have hindered the researchers from being able to find significance in the present context. Dudley and colleagues arrived at a similar conclusion in their recent investigation of RRI in collegiate runners. The researchers also had a sample size of 31 individuals from the same NCAA D1 cross country team and reported underpowered results when studying their sample's running characteristics in relation to injury prospectively (5). A more robust sample of athletes from teams with similar training regimen could be more effective in determining the quality of the MCS as a risk assessment tool. It should also be noted that the findings of this investigation cannot be generalized to the running population as a whole, given the lack of variability in participant demographics and training characteristics.

Further limiting the present investigation was the fact that the researchers did not have access to a comprehensive medical history of the participants. History of prior RRI is shown to place runners at a greater risk of becoming injured (17). Thus, adjustments were not made in the statistical analysis to control for the injury history of the athletes screened.

Lack of control for nutritional factors was a limiting factor. In performing a separate statistical analysis without including individuals who experienced bone injuries, the researchers attempted to minimize the impact of this potentially confounding variable. However, there was still no significance found in the analysis and it is still uncertain whether factors such as bone mineral density or iron status of the athlete may have played a role in the investigation.

Factors leading to running-related injury are complex and multifactorial. This complexity makes it difficult to identify the exact cause of any given injury. While the 3-D markerless motion capture system was not found to be a valid means of identifying RRI risk factors in the present study, future investigations with larger samples, more controls for known risk factors, and isolation of lower limb movement characteristics may yield significant findings.

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