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Investigation of a Three-Week Neuromuscular Training Intervention on Biomechanical Parameters of the Lower Quarter in Female Collegiate Pivoting Athletes

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Abstract

Background/Purpose: Mounting evidence has illuminated the efficacy of neuromuscular training (NMT) interventions to improve biomechanics related to anterior cruciate ligament (ACL) injury during dynamic pivoting movements. This investigation examined the strength, dynamic balance, and biomechanics of the lower quarter during select functional movement assessments in female collegiate athletes before and after a three-week NMT intervention with additional investigation of the influence of the training on a power-based motion correlated to sport performance. **Study Design:** Non-randomized Controlled Follow-up Study. **Methods:** 17 Division I NCAA female soccer players aged 18 - 21 participated, averaging a height of 167.79 cm and weight of 65.87 kg. Hip strength was measured with hand dynamometry. Single-leg stance modified balance (SLS^M) was measured with eyes closed and in static heel rise conditions. A Noraxon MyoMotion system assessed peak hip and knee excursion during select movement assessments. Vertical jump height was recorded. Six one-hour NMT sessions for lower quarter training were performed over three weeks. Tests were then repeated. **Results:** Significant improvements on post-intervention were found in hip abduction strength bilaterally ($p = 0.000$) and hip extension strength in both right ($p = 0.002$) and left ($p = 0.000$) lower extremities. Analysis of data also revealed significant improvements in SLS^M with eyes-closed for the right lower extremity ($p = 0.002$) and left ($p = 0.000$), as well as SLS^M with heel rise bilaterally ($p = 0.000$). Vertical jump height improved significantly ($p = 0.000$). Hip abduction ROM during single-leg squat ($p = 0.001$) and knee flexion during single-leg jump tests ($p = 0.001$) also increased significantly in post-intervention.

Conclusions: Following the NMT intervention, proximal hip strength, balance, and power with vertical jump significantly improved, indicating positive neuromuscular adaptations in the lower quarter. The MyoMotion system identified improved kinematics during single-leg squat and single-leg jump as demonstrated by increased knee flexion and hip abduction ROM, which is associated with decreased risk of ACL injury. These findings support the hypothesis that three weeks of NMT is sufficient to positively influence the lower quarter biomechanical profiles of female collegiate athletes and can facilitate performance enhancements in this population.

Subject Areas

Biophysics

Keywords

Neuromuscular Training, Anterior Cruciate Ligament (ACL), Biomechanics, Functional Movement, Injury Prevention, Sport Performance, Motion Analysis, Performance Enhancement

1. Introduction

Each year in the United States alone, over 250,000 anterior cruciate ligament (ACL) injuries occur, accompanied by an average annual cost of over two billion dollars [1] [2]. Over 70% of these injuries are non-contact in origin, meaning no opposing contact from another player or the environment is linked to the cause of injury [2]. Of the annual reported ACL injuries, only approximately 65% of athletes injured are able to return to full participation in sport, while just 55% return to their highest competitive level within that sport [3]. Regardless of whether an individual fully returns to sport, trauma from an ACL injury is well known to have significant long-term adverse effects, including a high probability of early-onset osteoarthritis, difficulty with general routine loading actions of the lower quarter across a number of instrumental activities of daily living, and range of potential detriments to psychological health [2] [4]. As we appreciate the degree to which the cumulative short and long-term effects impact those who suffer from ACL trauma, it becomes increasingly apparent that the development and implementation of efficacious preventative training programs is vital for optimizing the longevity and sustained health of dynamic pivoting athletes. Amongst these interventional pathways, neuromuscular training (NMT) has risen to the level of gold standard due the characteristic ways in which multiple dimensions of function are addressed in its implementation which distinguish it from strength training alone.

Ideal NMT interventions are multifaceted in nature and are designed to develop not only strength, but also proprioceptive control, neural drive, neuromuscular endurance, and motor sequencing capacities associated with complex movement behavior in a manner that facilitates the attenuation of provocative loading on vulnerable structures of the musculoskeletal system, such as the ACL [1] [5] [6] [7]. NMT interventions have a strong emphasis on skill acquisition, and as such are tied inextricably to principles that govern all learning, especially as they relate to biology of the brain and central nervous system. Further, when successfully employed, performance enhancements often emerge in concert with the intended kinematic and biomechanical changes associated with decreased risk for injury. The present investigation examines the outcomes of clinically based assessments for injury risk including strength, balance, and motor control in parallel with a more traditional metric of performance, vertical jump height.

Pathomechanics of ACL Injury

ACL trauma can occur in various ways, and is most often reported as a result of deceleration moments in the tibiofemoral complex with either 1) the knee extended and the foot planted, resulting in excessive anterior translation of the tibia on the femur (often complicated by tibial rotation moments), or 2) in the dynamic valgus collapse position involving adduction and internal rotation of the femur in combination with any degree of tibial rotation and abduction away from midline while the foot is planted on a fixed surface in the closed-kinetic-chain (CKC) [2]. When an individual changes direction from either of these positions, extreme torsional forces are applied to the ACL, which greatly elevate the risk for damage or rupture [2]. These two biomechanical patterns of high-risk movement each play critical roles in increasing vulnerability to ACL injury, and emerge with varying degrees of magnitude during many routine movements of the lower quarter. Distinctive functional loading activities that are common in dynamic pivoting sports include jumping, cutting/rapid change of direction actions, and landing, all of which can place the ACL at increased risk for damage, especially in young female athletes who demonstrate behavioral tendencies towards high-risk patterns of movement [2] [5]. Several studies have demonstrated that female athletes are 2 - 10 times more prone to ACL injury relative to their male counterparts, with increased risk arising as a consequence of several variables including anatomical, hormonal, environmental, biomechanical, and neuromuscular factors [1] [2]. While many of these risk factors are non-modifiable in current medicine, biomechanical and neuromuscular factors are considered modifiable in nature. Such factors can be influenced interventionally to facilitate more efficient force distribution throughout the musculoskeletal system in a manner that attenuates excessive strain to passive structures that are vulnerable to trauma. This subsequently decreases the likelihood of injury by transforming behavioral movement strategies away from key high-risk patterns of movement [2] [5] [8].

In comparison to males, females are more likely to land using a quadriceps-dominant strategy, involving suboptimal gluteal-to-quadriceps and hamstring-to-quadriceps force output ratios, relying heavily on the quadriceps to control deceleration and thereby contributing to shear forces that significantly stress the ACL [2]. Insufficient hip and knee flexion angles associated with "stiff landing" patterns have been shown to promote anterior translation of the tibia during dynamic CKC loading moments, in part due to quadriceps-dominant patterns of motor recruitment. In turn, a stiff landing pattern can yield substantial strain on the ACL [5] [6]. **Image 1** below illustrates a quadriceps-dominant landing pattern.

Additional biomechanical analyses have demonstrated that combinations of anterior tibial force and internal tibial torque near full extension put the ACL at high risk for injury [9] [10]. Conversely, a "soft landing" technique, characterized by optimal hip and knee flexion joint excursion and peak range of motion angles during landing, has been shown to diminish excessive force distribution through the ACL. The movement behavior of a soft landing is often referred to as a "hip strategy" because of the relative increase in gluteal muscle recruitment during loading, as demonstrated by EMG studies [2] [6]. In addition to the stiff landing predisposition commonly exhibited by females, valgus alignment during dynamic CKC loading is the other primary area of concern highlighted in this manuscript, a phenomenon which again is observed with greater frequency and magnitude in females as compared to males [11]. Knee valgus patterns of loading have been shown to be significantly larger in females for several reasons, including wider anatomical architecture of the female hip complex, increased femoral anteversion, increased Q angle, excessive tibial torsion, and excessive subtalar pronation in females relative to male counterparts [2]. Further, females have been shown to have a smaller intercondylar notch in addition to a smaller diameter ACL, which could result in impingement and contribute to increased

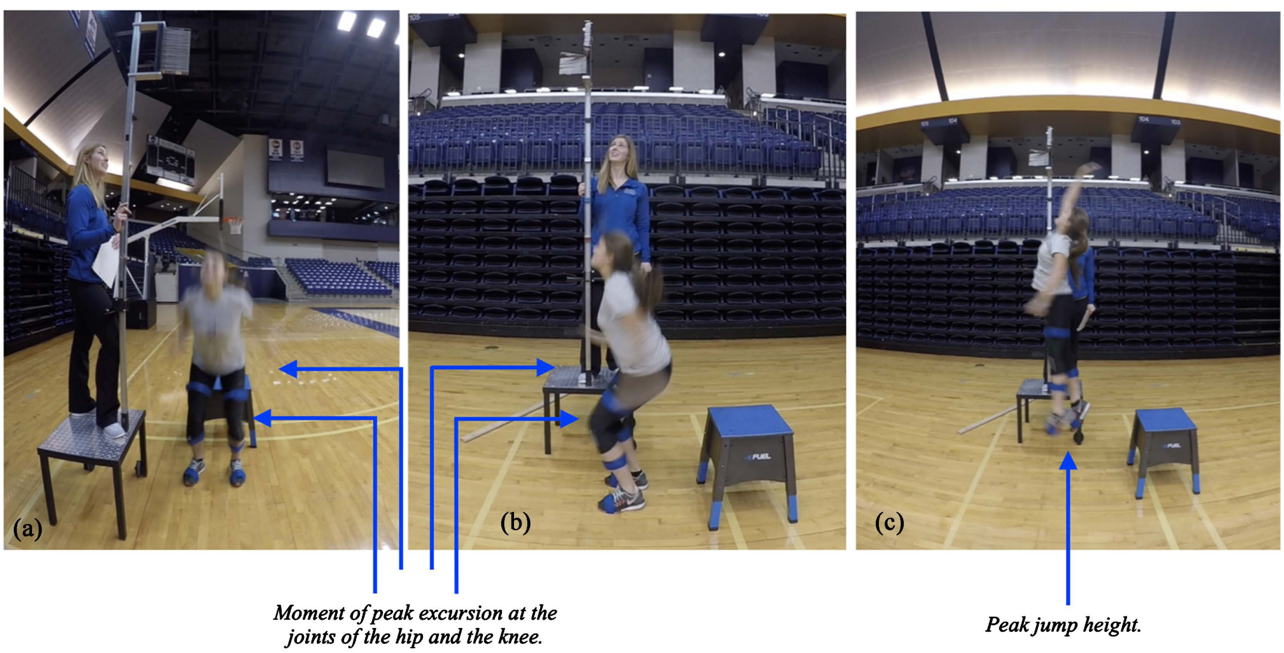


Image 1. Drop-jump test depicted. Landing posture in moment of peak joint excursion at first landing prior to concentric phase of maximal bilateral jump action shown in front (a) and lateral (b) views, followed by lateral view of the moment at which peak vertical jump height is reached (c). Peak joint excursion angles in this example illustrate a quadriceps-dominant landing strategy.

valgus loading [2].

The defining features of dynamic valgus collapse include excessive femoral adduction towards midline in combination with hip internal rotation and/or tibial rotation [9]. Risk of ACL injury increases as these angles become more pronounced. The high risk movement behavior in both stiff landing strategies and valgus collapse can be exhibited in a wide range of CKC movements, including high velocity changes of direction, pivoting, and deceleration tasks associated with the demands of sport performance. **Image 2** illustrates high magnitude dynamic valgus collapse that was identified during testing of one of the athletes assessed in a prior investigation with adolescent female athletes [12].

While many risk factors described in the literature are non-modifiable in nature, interventional strategies can be utilized to effectively address modifiable neuromuscular risk factors associated with the stiff landing and dynamic valgus collapse in order to optimize efficiency of CKC loading and subsequently reduce risk of injury [12] [13]. Generally, it is considered best practice to address modifiable risk factors in early adolescence, as individuals are undergoing major growth periods through this time and arguably have the greatest need and potential for improvement with training [14]. It remains warranted however to address to the full extent possible relevant dysfunction when identified across the age continuum. Although comparatively less is known about the degree to which movement behavior optimization can be achieved with training in collegiate level athletes as contrasted with youth athletes, the high rate of ACL injury in collegiate athletes warrants the implementation of effective interventions to mitigate such risk. Training interventions that improve function, decrease injury risk, and remain cost-effective for athletes across the developmental spectrum from youth to full maturity have arguably the highest utility and potential for being provided to the largest number of individuals in a rapidly growing landscape of athletes in need [15].

With recent advancements in motion analysis, the development of intervention strategies to address biomechanical dysfunction has become a major field of research. Traditionally, the focus of injury prevention programs has been on

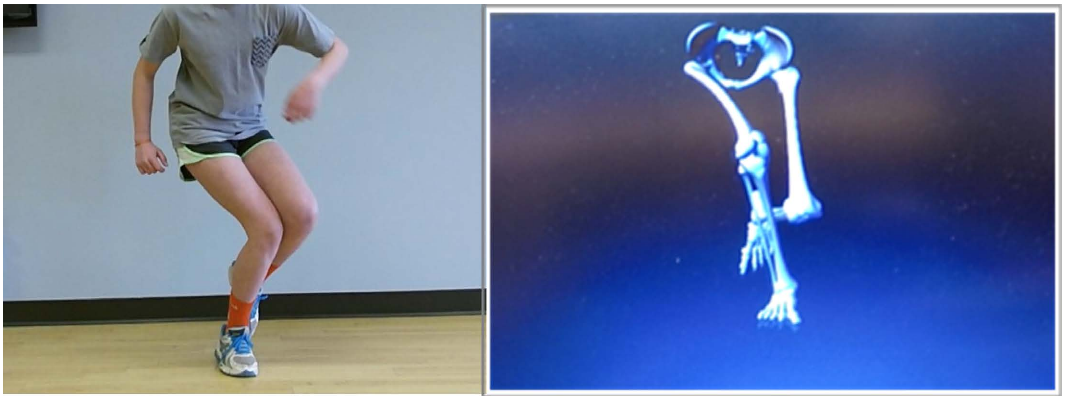


Image 2. The dynamic valgus collapse, presenting during a single leg squat assessment; case 1, video capture (left), and case 2, MyoMotion capture (right).

strength training of the lower quarter, an approach that has been shown to be effective to a considerable degree in isolation [16] [17]. However, this approach is limited in that high-risk patterns of movement that occur with alarming frequency are generally not addressed specifically with such strengthening alone, and therefore vulnerabilities related to these patterns can be left unresolved. While a well-rounded strengthening program is certainly better than no program of any kind, NMT interventions appear to offer the highest degree of benefit for pivoting athletes in a manner which more comprehensively addresses the multidimensional aspects of human movement and the constituent neuromuscular requirements therein.

At this time, a great deal of research describing the mechanisms of ACL injury has been published and widely distributed, whereas far less is available describing the degree to which interventional NMT programs can combat and counteract these well established causes of injury. Further, traditional training programs typically range from eight to twelve weeks in duration based on the physiological assumption that muscle hypertrophy does not morphologically occur until at least eight weeks of specific strength training has been implemented [16]. It must be recognized, however, that neuromuscular force output adaptations can be produced on surprisingly brief timescales when sufficient stimulus is provided. Further, strength measurements alone are insufficient to adequately predict performance in many dynamic coordinated CKC loading challenges of the lower quarter due to the complex nature and degree of motor control requirements of such movement [14] [18] [19]. Compellingly, recent research has demonstrated that improvements in the force output capacity of contractile structures can be achieved in response to resistance training prior to measurable muscle hypertrophy, which can develop well in advance of the 6 to 8 week time period which is typically assumed as a minimum amount for developing strength [16] [20]. These improvements are believed to occur as a result of centrally-mediated adaptations in efferent neural drive and rate of force development, lending credibility to the hypothesis that meaningful training adaptations can be elicited in athletes on condensed timelines [16] [20] [21]. Some evidence suggests that morphological muscular adaptations may begin to emerge in as little as four weeks of training at earliest [19]. With this in consideration, the training design for the present 3-week NMT intervention was created in efforts to further highlight the degree to which centrally-mediated neural drive supports complex movement.

Due to the alarming rates of incidence of ACL trauma in pivoting athletes and the enormous consequences that follow from such injury, there is a clear need for effective training programs to be provided for athletes at every age. Over the years, it has been shown that preventive training programs in young athletes can significantly reduce the incidence of ACL injuries [1] [5]. In a recent meta-analysis by Donnell-Fink *et al.*, ACL injuries were reported to decrease by 50.7% with the implementation of neuromuscular and proprioceptive training programs [1]. Of these prevention programs, it has been found that the combination of NMT, plyometrics, and strength training have most optimally yielded significant results in the reduction of ACL injuries [1] [5] [6] [15]. Age of the participant has also been shown to be a factor in the effectiveness of the prevention program, as prophylactic effects are generally greater in subjects that are 18 years and younger in contrast with those that are over 18 years old [6]. Given the relative paucity of research investigating the effects of NMT interventions in mature athletes over condensed training periods, the purpose of this study was to examine the movement behavior and neuromuscular profiles of experienced female collegiate athletes, and the extent to which an accelerated NMT intervention could positively influence the biomechanics of the lower quarter in this population over a three-week time period.

2. Methods

2.1. Subjects

Subjects for this study included 19 female collegiate soccer players between the ages of 18 - 21 who were chosen because of their participation in a Division I collegiate soccer program. To qualify for this study, subjects had to pass a basic preliminary lower quarter screening examination and be able to complete all required dynamic movement assessments without pain. This included the ability to squat, single-leg squat, jump bilaterally, and single-leg jump without pain. Exclusion criteria for participation were the inability to perform any of the aforementioned activities due to pain or injury. The athletes were assessed, then progressed through a three-week NMT program consisting of two training sessions per week each lasting an average of 75 minutes each in duration. Each athlete was then retested with the same procedures following the training intervention. Two subjects dropped out of the study due to injuries preventing them from performing the tasks required, resulting in a final data analysis describing the results for 17 subjects in total.

2.2. Instrumentation

A three-dimensional (3D) motion analysis system (Noraxon MR3 MyoMotion 3.8.6) was utilized to record biomechanics. The system has a measurement accuracy of 0.4 degrees for static measurements and 1.2 degrees for dynamic measurements. Signals occurring with movement were digitally recorded at 200 Hz. The researchers monitored sensor activity and signal transmission during data collection via sensors placed at the pelvis, left and right thighs, left and right legs, and left and right feet, respectively. Please see procedures for anatomical landmarks. The MyoMotion analysis software was operated through a Dell LATITUDE E5440 laptop computer. Standard treatment tables and a hand dynamometer (Lafayette Instrument Manual Muscle Tester Model 01165) were also used during manual muscle testing. A Vertec Vertical Jump measuring device (Vertec by Sports Imports, Columbus, OH) was used to record jump height.

2.3. Procedures

All procedures were approved by the Belmont University Institutional Review Board. Upon arrival, subjects completed the informed consent form and a medical history questionnaire. Subjects were started at random by time of arrival, with no regard to which subject started first or which station was completed first.

Station 1 included strength testing of both gluteus medius and gluteus maximus musculature bilaterally with use of the hand dynamometer. Manual muscle testing techniques were replicated from Daniels and Worthingham's Muscle Testing textbook [22]. To test the gluteus maximus for hip extension force output, the subject was positioned in prone with the test extremity in 90˚ of knee flexion. The hand dynamometer was placed on the posterior thigh approximately five inches proximal to the knee while participants were instructed to maximally extend their hip by lifting into the dynamometer. To test the gluteus medius for hip abduction force output, subjects were placed in a side-lying position and instructed to abduct their top-facing lower extremity while in an alignment of slight hip extension. The hand dynamometer was placed at the distal femur approximately five inches proximal to the knee. Prior to testing, each subject was instructed on proper performance of the motion, taken through the motion passively, and instructed to generate maximal exertion. Each contraction was held for 5 seconds, and the peak force was recorded. Subjects performed each movement three times and a best score was recorded for both abduction and extension in each lower extremity.

Station 2 included a series of single-leg balance assessments performed in a modified stance position of approximately 15˚ - 20˚ of hip and knee flexion of the stance limb with the contralateral limb in a non-weight-bearing position. Participants were instructed to maintain balance in this modified position on each side with eyes open and then again with eyes closed. An official attempt was documented when balance time exceeded two seconds. The trial ended when any of the following occurred: the non-weight bearing limb touched the ground, the stance limb was displaced from its original starting position, or the eyes were opened to re-establish orientation. A final balance test was then recorded for each limb in a single-leg heel rise position with the ankle in maximum plantar flexion so that only the ball of the foot and the digits were in contact with the floor. Testing was concluded when the contralateral limb touched the floor or when form was compromised in the single-leg heel rise position of the weight-bearing extremity.

In Station 3, participants completed a series of specific movement assessments involving dynamic functional loading of the lower quarter while wearing the MyoMotion sensors. Sensors were placed at the following locations on each subject: left and right thighs (five inches distal to the greater trochanter, over the iliotibial tract and facing outward), the left and right legs (half-way down the shin over the anterior tibialis), the left and right feet (securely taped to the dorsum of the foot over the 2nd and 3rd metatarsal base), and at the pelvis (worn as a belt with the sensor directly over the sacrum). Each sensor was reinforced with athletic tape to ensure stable placement and to avoid movement while jumping. A calibration file was obtained prior to each movement test. The subjects were instructed to stand erect and still for this calibration. Once calibrated, the subject performed a series of ten squats, ten single-leg squats on each leg, ten single-leg jumps on each leg, and three maximal vertical leaps in a drop jump test format. Maximal vertical jump height was captured using a Vertec Vertical Jump measuring device for each repetition of the drop jump test, and the highest score was recorded for data analysis for each athlete. For each functional motion, the angles of all three planes of the hip were recorded at peak knee flexion angle. The subjects were allowed to take a brief standing break in between each skill, as needed. All motions were recorded and saved in the Dell computer through MyoMotion software. Each of the 53 repetitions the subject performed was recorded and included in statistical testing. In both pre-and post-intervention conditions, the participants completed the examinations in a randomized order.

The NMT intervention was implemented successively over three consecutive weeks on a two-session per week basis with the participants organized collectively as a group. The training began with isolated strengthening and progressions advanced through a series of balance and exercise-based neuromuscular re-education techniques, integrating regionally coordinated movements with isotonic and isometric strengthening while coordinating balance challenges in a progressive fashion over the three week period. Varying open and closed-chain combinatorial movements were performed in weight-bearing positions with elastic resistance bands placed just proximal to tibiofemoral joints as pictured in Image 3. A fatigue model was employed for prescriptive purposes which dictated that the participants complete each strengthening activity up until the onset of healthy muscle fatigue (not to failure), with the condition that neither pain emerged nor loss of sufficient technical form was observed.

The intervention progressed in stages of increasing complexity using a combination of the following tiers of training: 1) traditional isolated strengthening,

Image 3. Educational demonstration of correct mechanical alignment for single-leg squat with contralateral hip abduction.

2) dynamic balance training, 3) neuromuscular re-education, 4) plyometric training, and 5) functional mobility and recovery activities as follows. Isolated strengthening activities were directed towards classically deconditioned structures related to lower quarter functional movement, with special emphasis on targeting the proximal hip stabilizers bilaterally in sequences of hip abduction, external rotation, and extension against elastic tubing resistance (**Image 4**). Additional strength training was focused towards the transverse abdominis, lower rectus abdominis and obliques, hamstrings, gastrocnemius, soleus, and regional ankle stabilizers. Dynamic balance training activities were completed in single-leg stance with various depths of combined hip and knee flexion and varying amounts of visual occlusion (eyes-open and eyes-closed training conditions). Neuromuscular re-education tasks were characterized by slow motion movement sequences and/or extended submaximal isometric holds performed in a range of open and closed chain postures, held for periods of 30 seconds to 3 minutes (activity, tolerance, and progress dependent), including the essential functional training pathways of squatting bilaterally and unilaterally, jump and landing sequences, cutting and pivoting, high-velocity deceleration, and other related complex combinatorial motor coordination tasks. Plyometric training activities including rate of force development techniques progressed into states of fatigue, beginning with small amplitude actions leading to large amplitude movements, incorporating the bilateral jump (counter-movement jump) and single-leg jump strategies.

For all weight bearing training pathways, a substantial amount of education was provided regarding effective utilization of stabilizing musculature with proper sequencing to develop optimal mechanics for bilateral and unilateral

(a)

(b)

Image 4. Reciprocal lateral leap training exercise against elastic tubing resistance (a), and lumbopelvic hip dissociation exercise with resisted hip extension against elastic tubing resistance (b).

squatting, deceleration, unilateral change of direction, and landing during various sport-specific activities. Major emphasis was placed on minimizing dynamic valgus collapse and facilitating soft landing strategies for ideal force attenuation during loading moments with the intent that athletes would integrate such strategies into the competitive environment. Finally, functional mobility and recovery activities were completed in all primary lower quarter muscle groups and trunk as warm-up, cool down, and active rest intervals to facilitate flexibility, preparedness, and tissue recovery. Dynamic stretches were utilized predominantly in earlier stages of a given session, whereas prolonged stretches were integrated at the end of sessions.

Throughout the intervention period, the participants were advised to utilize these new training techniques together as a team for regular warm-up before practice and additionally in 10 - 15 minutes intervals following their bi-weekly practice sessions. It was suggested that training techniques were completed prior to previously established final cool-down activities, which included general stretching and foam rolling techniques for the lower extremities. These supplementary practice activities were initiated beginning with the second week of training and maintained throughout the remainder of the intervention, confirmed weekly by verbal report of the players. These activities were encouraged to be continued additionally throughout the remainder of the regular soccer season in order to reinforce fundamental educational concepts, to maintain gains achieved in the training intervention, and to provide space for further training and development.

3. Results

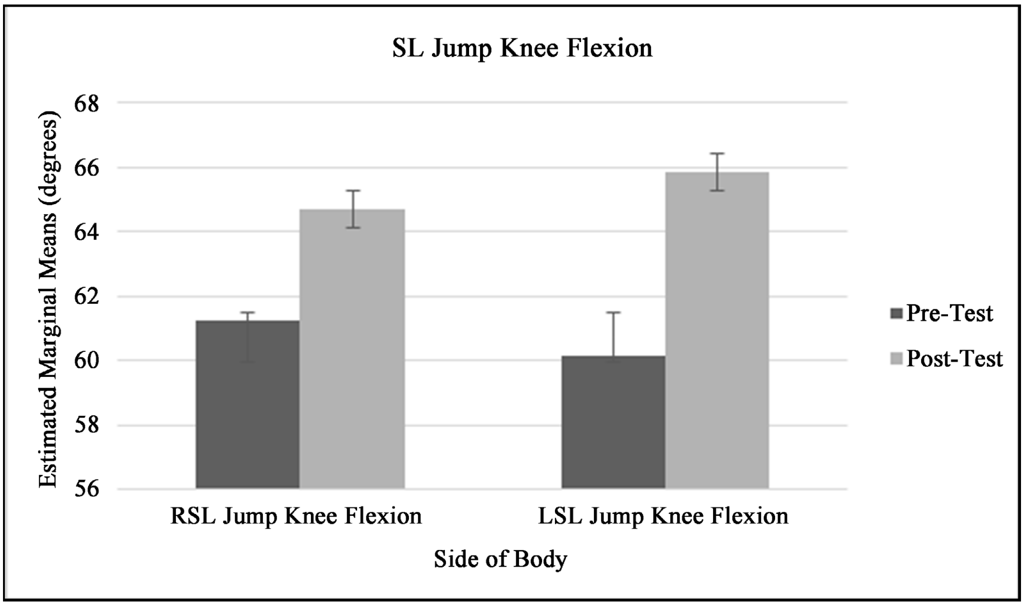
***MyoMotion Assessment*:** Peak range of motion for knee flexion, hip flexion, hip abduction, and hip external rotation was analyzed while performing bilateral squats, single-leg squats, single-leg jumps, and vertical jumps using two-way repeated measures ANOVA. The degrees of motion for each joint during the specific movements were measured during peak knee flexion because peak knee flexion represented the end of force absorption for a specific movement. The significance level was set a priori at 0.05. Refer to **Table 1** below for significance values for each of the respective assessments.

The MyoMotion data were analyzed using a two-way repeated measure ANOVA with time and side of the body as the two factors. The time factor examined the differences between pre-intervention values and post-intervention values. The side of body factor explored the differences between the right leg and the left leg during the four different movement patterns. Significance was found as a factor of time in hip abduction during the single-leg squat and knee flexion during the single-leg jump. During the single-leg jump, values for knee flexion increased post-intervention as compared to pre-intervention (**Table 1**, **Graph 1**). Hip abduction during the single-leg squat was increased significantly between the pre-intervention values and the post-intervention values (**Table 1**, **Graph 2**).

Table 1. Significance Values for MyoMotion Assessments.

Assessment	Kinematic Motion	Time	Side of body	Interaction
Bilateral Jump	Hip Flexion	0.812	0.012	0.624
	Hip Abduction	0.404	0.265	0.938
	Hip Rotation	0.474	0.336	0.471
	Knee Flexion	0.168	0.013	0.925
Single-Limb Squat	Hip Flexion	0.802	0.029	0.915
	Hip Abduction	0.001	0.219	0.239
	Hip Rotation	0.471	0.002	0.490
	Knee Flexion	0.815	0.161	0.688
Bilateral Squat	Hip Flexion	0.956	0.000	0.951
	Hip Abduction	0.828	0.483	0.091
	Hip Rotation	0.673	0.006	0.465
	Knee Flexion	0.256	0.000	0.700
Single-Limb Jump	Hip Flexion	0.408	0.053	0.388
	Hip Abduction	0.655	0.379	0.862
	Hip Rotation	0.784	0.001	0.099
	Knee Flexion	0.001	0.965	0.213

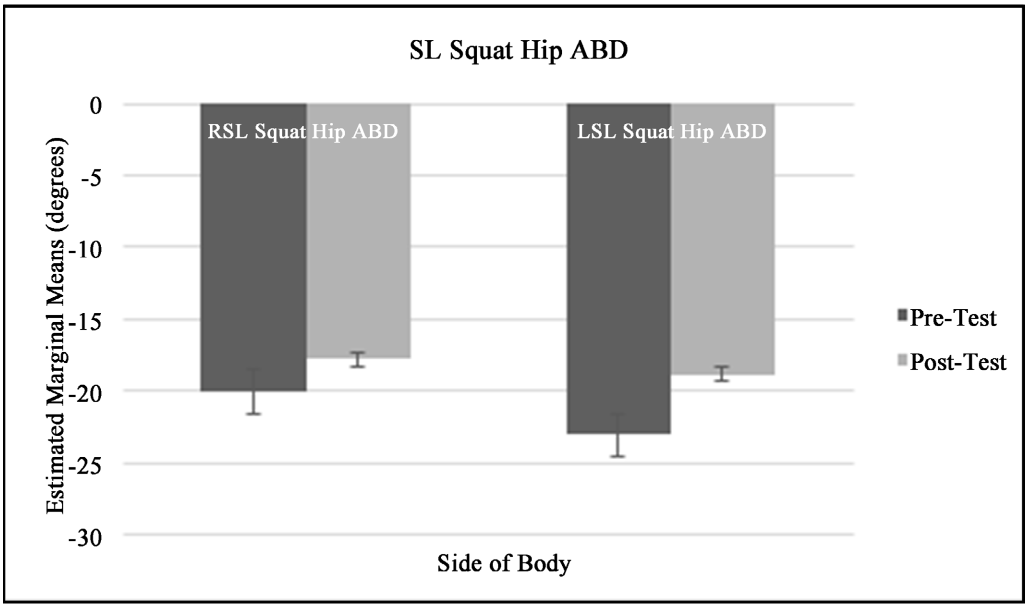
Significance as defined by $p < 0.05$.



Graph 1. SL Jump, Sagittal Plane Knee Flexion.

Strength Assessment: Pre-intervention and post-intervention measurements were also collected for hip abduction strength, hip extension strength, and vertical jump height. Data was then analyzed using a paired t-test. Right hip abduction strength ($p < 0.001$), left hip abduction strength ($p < 0.001$), right hip extension strength ($p = 0.003$), left hip extension strength ($p < 0.001$), and vertical jump height ($p < 0.001$) all significantly increased over the three-week NMT program compared to the values obtained before the training (Table 2, Table 3, Graph 3, Graph 4).

Balance Assessment: Data for balance assessments were analyzed using a paired t-test. As seen in Table 4 and Graph 5, significance was found between pre-intervention and post-intervention measures for each of the balance measures tested, with exception of SLS^M in the eyes-open condition in which participants all achieved the highest cutoff measurement time for both pre- and post-training assessments. SLS^M improved significantly in the eyes closed condition



Note: Negative values of hip abduction shown represent hip adduction range of motion excursion, with "0" demarcating the neutral hip position of nil degrees abduction and adduction, respectively.

Graph 2. SL squat, frontal plane hip abduction.

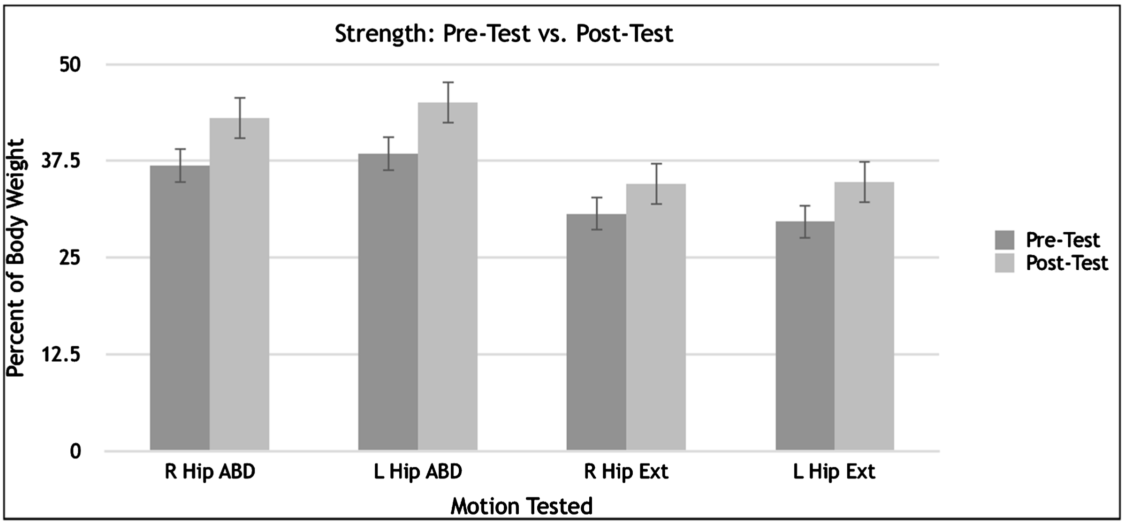
Table 2. Strength dynamometry assessments.

Assessment	Pre-Test Mean (%BW)	Post-test Mean (%BW)	Significance
R Hip Abduction	36.88	43.04	0.000
L Hip Abduction	38.44	45.00	0.000
R Hip Extension	30.69	34.56	0.003
L Hip Extension	29.63	34.81	0.000

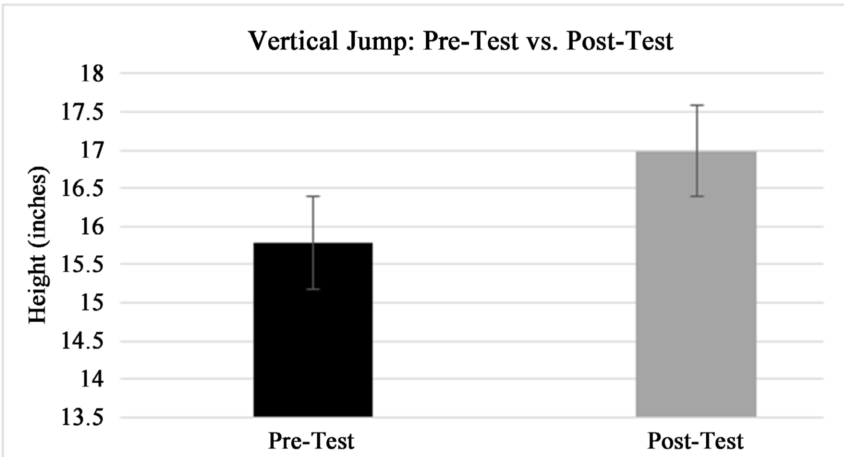
Significance as defined by $p < 0.05$; %BW = Percent of Body Weight.

Table 3. Vertical jump assessment.

Assessment	Pre-Test Mean (cm)	Post-test Mean (cm)	Significance
Vertical Jump Height	40.117	43.142	0.000



Graph 3. Hip strength assessment.



Pre-Test: 15.794 in (40.117 cm); Post-Test: 16.985 in (43.142 cm)

Graph 4. Vertical jump height.

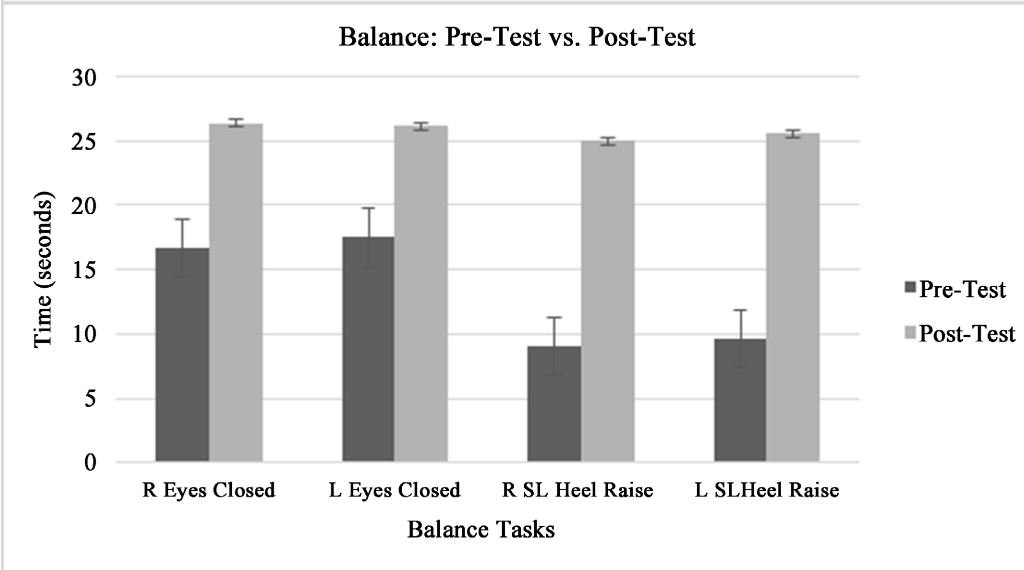
Table 4. Balance assessments.

Assessment	Pre-test Mean (s)	Post-test Mean (s)	Significance
R SLS^{M}, Eyes Closed	16.65	26.35	0.002
L SLS^{M}, Eyes Closed	17.47	26.12	0.000
R SL Heel Rise	9.00	24.94	0.000
L SL Heel Rise	9.59	25.53	0.000

for the right ($p = 0.002$) and left ($p < 0.001$) lower extremities, as well as in the single leg heel rise condition bilaterally ($p < 0.001$).

4. Discussion

While many studies indicate the need for at least 6 to 8 weeks of a training intervention for significant advantages to be imparted to any given population, the



Graph 5. Balance assessments.

results from the present study indicate that NMT interventions with durations as short as 3 weeks can produce significant improvements in strength, balance, jump height, and certain functional movement behaviors during dynamic lower quarter functional loading tasks in female collegiate pivoting athletes.

The findings from the present study challenge traditionally held notions that strength development as a result of progressive training can only occur if implemented over periods of 6 to 8 weeks in duration or greater. While the cyclical 6 to 8 week training structure has momentous implications related to the care and development of virtually all athletes who desire to sustain high levels of performance over extended periods of duration, significant barriers exist in efforts to reach all individuals who stand to benefit from such training. Limitations in time, financial resources, and skilled personnel interfere with our collective ability to bring vital injury prevention measures to an enormous variety of populations in need. The development of interventions which can elicit positive neuromuscular adaptations over condensed time periods may help bridge this gap and over time promote a decrease in the alarming incidence of serious musculoskeletal trauma across all populations.

Intelligently designed preventative NMT programs can effectively reach individuals of diversely populated athletic communities and help to provide a foundation for athletes to be supported throughout the course of their lifetime. While no intervention can fully abolish risk of serious injury for those pursuing athletic endeavors, it must be recognized the high degree of risk mitigation that can indeed be achieved with skilled training as well as the vast numbers of individuals who stand to benefit from such work but have yet to be reached. In efforts to help overcome the inherent challenges facing the field of sports medicine and to advance our understanding of human developmental potential in this setting, this study was designed to shed light on the degree to which an NMT intervention can influence the development of strength, dynamic balance, and motor control in fundamental movement behaviors of a competitive collegiate athletes on an unusually accelerated timeline.

The authors of the present study support the premise that a multifactorial, criterion-based clearance for sport participation should be adopted for practitioners in sports medicine and athletic training environments as part of a comprehensive, interdisciplinary approach to optimizing the quality and longevity of athletic endeavors. Motion analysis software and functional movement assessments elevate return to sport testing and injury prevention screening to higher levels of sophistication which can produce insight with respect to discerning magnitude of risk as well as the clinician's ability to track progress. The information gained from such evaluations may be used as a directive in guiding the development of each individual throughout their athletic careers with increasing degrees of specificity, ideally at regular intervals before each new season and more rigorously throughout the rehabilitation process after significant injury of any kind.

4.1. Strength Development

Strength training has been well established as an essential feature of injury prevention and training programs designed to care for athletes of all disciplines. An emerging line of inquiry in this domain involves the investigation of the extent to which positive neuromuscular adaptations can occur as a result of training interventions over condensed time periods. Due to the importance of the proximal hip stabilizing musculature of lower quarter pivoting athletes in attenuating risk of injury in addition to promoting efficient coordinated movement of the extremities, the researchers chose to focus on evaluating and training the strength capacity of two commonly deconditioned and/or inhibited primary gluteal hip stabilizers. Following the training intervention, all participants demonstrated significantly improved force production in these structures as determined by hand dynamometry testing, despite participating in only three weeks of deliberate training. These outcomes strongly support the hypothesis that improving neuromuscular force generation for any given movement can be facilitated by enhancing the signaling efficiency of motor neurons between the spinal cord and musculotendinous unit, a phenomenon described as neural drive, in time periods as little as three weeks. However, to the best knowledge of the present authors, a minimum dose threshold or ceiling effect for these processes to occur on a significant level has yet to be determined in the laboratory setting with similar condensed durations of training.

4.2. Developing Balance, Proprioception, and Spatial Awareness

The balance assessments performed for this study were completed in a distinguished manner relative to the traditional positioning often utilized in clinical and laboratory settings. Traditional positioning of single leg stance balance testing requires subjects to be positioned in upright standing in full hip and knee extension on the weight-bearing limb, maintaining the trunk in neutral alignment while the opposite lower extremity is displaced in a non-weight-bearing position. In contrast, the balance assessments utilized for the participants in this study were performed in a modified "athletic stance" position as described in the methods above, involving flexion of both the hip and the knee joints of the stance limb into a dynamic posture that minimizes the stabilization afforded by passive restraints of the knee complex when supporting the body with the knee locked in full extension. Positioning the subject in this manner subsequently requires greater active neuromuscular recruitment for upright postural control to be maintained, and thereby provides greater insight into the functional proprioceptive capacity of individuals being tested.

The researchers of this study posit that such positioning more accurately simulates the demands of athletic competition, and therefore performance during assessment in these conditions will more accurately reflect one's true skill level and functional coordination in unilateral loading postures, with a higher degree of sensitivity relative to the demands of dynamic pivoting sports. Training and assessment procedures in this condition, with the additional complexity of the removal of the visual stimuli in select circumstances, increases the demands on the proprioceptive and vestibular systems of balance, and thereby illuminates more clearly their functional capacity in any given environment. The complexity of maintaining balance in dynamic unilateral loading moments increases in real-world sporting environments. There is substantial utility in examining the quality of function in each of the complementary systems of balance when a substantial amount of cognitive resources dedicated to vision are occupied by the demands of in-play action and/or the field of vision itself is significantly obstructed.

A second balance assessment was introduced for this investigation which warrants very similar discussion due to its relative novelty in the research literature and the magnitude of improvement that was demonstrated by subjects following the training period in this study. While the majority of protective mechanisms related to injury prevention described in this study revolve around the examination of forces influencing the biomechanics of the hip-knee complex, an additional training goal of comprehensive lower-quarter NMT interventions should include protecting the ankle complex in parallel with the hip and knee, due to its relative vulnerability in tandem with routine dynamic loading. The single-leg heel rise balance assessment was introduced for use in this study as a novel assessment of both plantar flexor strength and endurance, as well as a measure of proprioceptive ability. While, to the best of the present authors' knowledge, at the time of this investigation there are no data available to indicate the efficacy or predictive value of this measure as an assessment tool, this investigation confirms the hypothesis that this specific form of dynamic balance at the ankle complex is susceptible to improvement with deliberate effort through NMT interventions.

Collectively, the outcomes identified in each of these balance measures as a result of the intervention strongly support the hypothesis that three weeks of NMT is sufficient to effectively improve the dynamic balance capabilities of female collegiate soccer players. With the modified conditions implemented for the balance assessments in this study, such outcomes may indicate a high level of transferability of skill acquisition from controlled training environments to the playing field, in contrast to alternative traditional balance assessments which are often much less complex and less functional in nature.

4.3. Motor Skill Development

A comprehensive training approach for athletes of any kind should include an explicit focus on the movement patterns specific to the individual's sport. Due to the increased complexity of such movement patterns in contrast to isolated muscle strengthening, it is expected that greater duration training periods will be more beneficial than those short in duration. Increased duration of cumulative training periods allow the time and space for adequate internalization of educational themes and central adaptations to emerge and be reinforced over time, providing an avenue for individuals to learn through structured practice in a progressive manner. This time-specific paradigm poses perhaps the most challenging barrier to overcome for any condensed duration training intervention, and is yet another reason why a long-term follow through approach is strongly encouraged when possible to integrate within each unique organizational body. In addition, periodized modifications that reinforce and build upon gains made in any initial training period should be utilized in a manner that most adeptly sets up each individual for the greatest chance of success in a manner that harmonizes with the technical and tactical demands of team performance. The authors of the present study recognize and fully endorse this principle.

Given the inherent difficulties of teaching new skills to athletes with years of previous training and the time requirements to fully optimize movement behavior for any given skill of high complexity, it is very promising to note the positive adaptations that did emerge in the population examined for this study. In particular, the improvements in proximal hip strength and fine motor control during unilateral CKC loading assessments appeared to facilitate a decrease in dynamic valgus collapse of the tibiofemoral complex and an overall reduction in valgus loading moments. This phenomenon was observed most prominently during the single leg squat test by the athletes' demonstration of sustained control of femoral abduction towards the neutral hip position during this task, relative to their pre-training performance levels. Further, the increase in knee flexion achieved with landing during the single leg jump task is strongly indicative of the acquisition of a more efficient, less provocative ("soft") landing pattern, in turn providing a protective mechanism to knee structures. As described earlier in this manuscript, previous research has shown that decreased hip and knee flexion angles exhibited during landing moments in the lower quarter leads to greater strain on the ACL in addition to other regional passive restraints of the musculoskeletal system. Similarly, the ACL is also stressed maximally with increasing hip adduction and internal rotation moments as they contribute to valgus positioning of the tibiofemoral complex during dynamic closed kinematic chain loading actions of the lower quarter. These specific movements have been linked to increased risk of ACL trauma [6] [9], and therefore constructive development away from these high-risk patterns should qualitatively be viewed as a positive training outcome.

The results of the present study support the hypothesis that a condensed duration training period of three weeks in Division I collegiate female soccer players is sufficient to significantly influence functional movement patterns. The positive adaptations that emerged as a result of the training intervention are encouraging findings due to the clear role that strength, balance, and biomechanics have in supporting the high volume of complex loading demands during competitive sport training and performance. The fact that such changes emerged in such a relatively short duration of training is a remarkable finding, which warrants further investigation into the full extent that such interventions can be beneficial at each stage of athletic development. The present authors continue to support the traditional notion that intensive preventative training programs should take place over a duration of at least 6 to 8 weeks when possible, in order to yield the most robust neuromuscular adaptation effects. However, the present study suggests that three weeks of NMT intervention is advantageous, when 6 to 8 weeks or greater is not possible.

As promising as the improvements found in this study are, the upper ceiling of maximal gains that may be achieved with similar intensive training in these specific measures has yet to be discovered. It must be noted that this is only a pilot investigation with the limitations in statistical power of a single team training design with only 17 individuals and the limited access of only 6 total training days in this trial. Future investigations could potentially yield even greater improvements with greater exposure to interventional techniques with the participants within the same time period, manipulating variables such as training session frequency and duration. Naturally, the results of the present study are only immediately generalizable to female collegiate soccer players. Continued research is necessary to explore the effect of such an intervention across different ages, genders, and sport domains.

Finally, it must be stated that the outcomes of the present study only indicate the short-term gains made over a three-week training period with this population. Although the participants and coaching staff were provided with training and educational resources to utilize after the intervention period to reinforce the gains achieved in the pre-season interval throughout the competitive season, no current data are available to describe the stability of the improvements initially achieved in this study over the long-term. Any such enhancement in dynamic function as those described in this study stand to benefit from reinforcement with continued NMT-based interventional activities to maintain and build upon improvements achieved.

Regardless of the outcomes of this study or any assessment of NMT interventions with similarities to this investigation of any kind, it should most certainly be recognized and emphasized that the long-term care of any athletically-inclined individual should involve a comprehensive, long-term approach with a multifaceted periodization framework, designed with the greatest possible degree of specificity relative to the sport of participation. Implementing reliable injury tracking mechanisms for comparative analysis following NMT interventions may potentially further validate the utility of such training, and delineate which populations stand to benefit the most from them with future integration into organizations and communities at various levels. Investigation into this realm of subject matter holds significant potential value to all participants in the athletic community, and may in the future lead to important advances in a variety of interdisciplinary fields. Continued research is warranted to further illuminate the full extent of all neuromuscular adaptations that may be achieved with similar interventions over such condensed time periods as described in this study. Future investigations should examine which combinations of training techniques are most effective in meeting athletes across the developmental spectrum at an appropriate challenge level relative to their state of development.

5. Conclusions

The purpose of this study was to determine if a three-week NMT intervention could influence the biomechanical profiles of female Division I collegiate soccer players over the Spring season training period. The results obtained indicate that following the intervention, measures of proximal hip strength, balance, vertical jump height, and some, but not all, qualitative components of dynamic functional loading can be significantly improved in Division I female soccer players, suggesting the emergence of positive neuromuscular adaptation effects that contribute to the optimization of these athletes' biomechanical profiles. The MyoMotion inertial tracking system utilized in this study effectively demonstrated the extent to which the functional kinematics of single-leg squat and single-leg jump improved with NMT for this population over the intervention period, while identifying areas which warrant additional therapeutic intervention at various stages across the continuum of care. While it is evident that long-term intervention periods are most beneficial to achieve peak developmental potential for athletes, the findings of this investigation support the hypothesis that the biomechanical profile of female collegiate dynamic pivoting athletes can be significantly enhanced following NMT periods of as little as three weeks in duration.

Despite intensive research efforts to address ACL injuries in athletic populations, incidents of trauma are still occurring at alarmingly high rates; there is a pressing need to develop and build upon strategies which stimulate the widespread implementation and maintenance of evidence-based NMT programs [23]

[24]. Given the physiological requirements for strength and motor control to develop and effectively integrate into long-term transformations, continued training following any condensed training period is warranted to reinforce any improvements yielded from initial training, address any areas of concern that may have yet to be resolved, and potentially improve aspects of performance more broadly. Effects of greater magnitude may be observed with a mirrored approach towards the care of higher-risk populations such as adolescent female athletes, where baseline neuromuscular capabilities are generally much lower and therefore there is greater room for development. Future research should investigate the extent of effects of NMT interventions with varying durations at each stage of the developmental continuum, and all such studies stand to provide greater value when combined with reliable injury tracking mechanisms for comparative analysis in the long term. The outcomes of this study add to our understanding of the role of preventative NMT interventions in improving the biomechanical profiles of dynamic pivoting athletes, in addition to supporting the notion that inertial tracking systems may be used as a complementary screening tool for identifying suboptimal biomechanics in athletic individuals.

Conflicts of Interest

The authors of this investigation declare no conflict of interest in the conduction or presentation of this research. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report.

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