Motor learning methods that induce high practice variability reduce kinematic and kinetic risk factors of non-contact ACL injury

Abstract

The prevention of non-contact anterior cruciate ligament (ACL) injuries often involves movement training, but the effectiveness of different motor learning methods has not been fully investigated . The purpose of this study was therefore to examine the effects of linear pedagogy (LP), nonlinear pedagogy (NLP) and differential learning (DL) motor learning methods on changing kinetic and kinematic factors during expected sidestep cutting related to non-contact ACL injuries. These methods primarily differ in the amount and type of movement variability they induce during practice. Sixty-six beginner male soccer players (27.5 ± 2.7 years, 180.6 ± 4.9 cm, 78.2 ± 4.6 kg) were randomly allocated to a group that trained for 12 weeks with either a LP, NLP or DL type of motor learning methods. All participants completed a biomechanical evaluation of side-step cutting before and after the training period. Analysis of covariance was used to compare post-testing outcomes among the groups while accounting for group differences in baseline performance. Changes in all kinematic and kinetic variables in NLP and DL groups were significantly higher compared to the LP group. Most comparisons were also different between NLP and DL group with the exception of vertical ground reaction force, the knee extension/flexion, knee valgus, and ankle dorsiflexion moments. Our findings indicate that beginner male soccer players may benefit from training programs incorporating NLP or DL versus LP to lower biomechanical factors associated with non-contact ACL injury, most likely because of the associated increased execution variability during training. We discuss that practitioners should consider using the NLP or DL methods, and particular the NLP, during which variability is induced to guide search, when implementing training programs to prevent ACL injuries in soccer.

Keywords: anterior cruciate ligament injuries, motor learning strategy, beginner, soccer

Highlights

Motor learning methods are effective in reducing kinetic and kinematic risk factors of non-contact ACL injury among beginner footballers

Increasing movement variability during training is an effective factor in reducing ACL injury

Nonlinear pedagogy and differential learning methods both resulted in larger joint flexions and reduced vertical ground reaction force

1.0 Introduction

Injuries to the knee are most prevalent in soccer (Chomiak, Junge, Peterson, & Dvorak, 2016). The most common knee ligament injury is to the anterior cruciate ligament (ACL), which originates in about 70% from non-contact actions or situations such as cutting and rotational movements (Chomiak et al., 2016; Johnston et al., 2018). Although females maintain ACL injuries at higher rates, the number of ACL injuries in males may be similar with greater participation in physical activity (Sanders et al., 2016). There is also evidence to suggest that beginners are more likely to be injured in sports such as soccer (Chomiak et al., 2016). ACL weaknesses and injury are associated with reduced static and dynamic stability of the knee and lower extremities, hampering defective sensory feedback in the injured knee. This can lower the overall function of the knee joint and cause secondary injuries, such as osteoarthritis or meniscus rupture, as well as mental and psychological problems (Caraffa, Cerulli, Projetti, Aisa, & Rizzo, 1996; Petushek, Sugimoto, Stoolmiller, Smith, & Myer, 2019). The results of a meta-analysis revealed only 55% of non-elite athletes who sustained an ACL injury return to competitive level sport (Ardern, Taylor, Feller, & Webster, 2014). Thus, it is essential to try to better understand and address factors associated with ACL injury (Caraffa et al., 1996; Johnston et al., 2018).

Sidestep cutting is a common action associated with non-contact ACL injury in a number of sports (Montgomery et al., 2018; Olsen, Myklebust, Engebretsen, & Bahr, 2004; Waldén et al., 2015). During sidestep cutting high knee joint loads are generated (i.e., anterior shear force, external abduction and rotation moments) (McLean, Su, & van den Bogert, 2003) that increase ACL strain (Shin, Chaudhari, & Andriacchi, 2009, 2011). Several kinematic and kinetic factors such as increased lateral trunk flexion over the support leg, less knee flexion at initial contact and during the support phase, greater initial knee abduction angle, greater lateral plant leg distance and greater initial hip internal rotation and abduction have been found to associate with greater peak knee abduction moments (Havens & Sigward, 2015; Jones, Herrington, & Graham-Smith, 2015). These knee abduction moments are often used as a surrogate measure of non-contact ACL injury risk. Thus, attention to addressing side-step cutting technique (movement [re-]training) based on the abovementioned findings provides an opportunity to reduce knee joint loads and potentially mitigate non-contact ACL injury risk (Dos'Santos, McBurnie, Comfort, & Jones, 2019; P A Jones, Barber, & Smith, 2015).

Movement (re-)training is an important ACL injury prevention strategy. Traditionally, greater overall flexion is desirable, such that impact forces are reduced and more of the load during weight acceptance is carried by muscular contraction rather than by ligaments. Also limiting non-sagittal plane motion such as the dynamic knee valgus motion (combined internal hip rotation, knee abduction & external rotation) would be desirable (Benjaminse, Otten, Gokeler, Diercks, & Lemmink, 2017; Crenshaw, Pollo, & Calton, 2000; Hewett et al., 2005). This movement (re-)training relies on effective motor learning approaches. Methods that allow for training- and teaching-induced variability are proposed to facilitate adaptive movements, as practice variability increases the number of degrees of freedom (DOF) incorporated in movement control (Dhawale, Smith, & Ölveczky, 2017; Newell & McDonald, 1994). Increased DOF improves functionality by allowing adaptation to the dynamic environment, which is expected to reduce injury risk (Bartlett, Wheat, & Robins, 2007). A method that facilitates variability can help increase joint flexion so that impact forces are distributed across the muscles and overall ground reaction forces reduced, leaving the ligaments less at risk of getting damaged from excessive forces. Several perspectives and methods about inducing variability during training are distinguished (see also, Ranganathan & Newell, 2013): linear pedagogy (LP, e.g., Adams, 1971), which considers execution and task goal variability as noise and thus undesirable; and nonlinear pedagogy (NLP, e.g., Chow, 2013) and differential learning (DL, e.g.,Schollhorn, Hegen, & Davids, 2012), which both consider variability as functional, with DL being the more extreme in not only encouraging execution variability during training, as proposed by NLP, but also task goal variability.

The LP strives for a universal, ideal movement pattern for everyone, ignoring differences in individual learners' action systems and learning histories. It uses models, instructions and feedback and repetitive practice to instill the ideal movement pattern. Variability, as deviations from the ideal movement pattern, is considered as noise and thus needs to be reduced (Adams, 1971; Fitts & Posner, 1967; Schmidt, Lee, Winstein, Wulf, & Zelaznik, 2018). In contrast, in NLP and DL methods, inducing variability is considered necessary for learning. In these methods, variability is critical for allowing performers to find their individual flexible movement patterns to become adaptive in an ever changing environment (Chow, 2013; Ranganathan & Newell, 2013). Yet, although both NLP and DL emphasize the critical importance of variability for learning, they conceive the type and role of variability differently. Within NLP variability is induced in the performance to guide the learner' search for individual movement solutions, as such, variability is semi-structured (i.e., colored noise). By contrast, within DL variability serves to add random fluctuations (i.e., white noise) to the performance to experience as many as possible movement solutions. Mostly, DL methods are prescriptive in terms of an instructor being present who provides the performer with many different ways (maximum variation) to achieve the task goal, preferably ensuring that no attempt will be alike the previous ones. The instructor mostly tells the actor what to do with no feedback provided, although also environmental and task constraints can be manipulated (Schollhorn et al., 2012; Savelsbergh, Kamper, Rabius, De Koning, & Schöllhorn, 2010). NLP is typically less prescriptive and allows a more active self-regulated search from the performer by manipulating situational constraints (i.e., both adding and taking away). The aim of increasing variability not to maximize it for the performer to experience as many solutions as possible, as per DL, but to encourage and guide the performer to actively explore multiple movement solutions. This active self-regulated exploration leads to finding multiple individual movement patterns or degeneracy, making performance adaptive and smooth (Chow, 2013; Ranganathan & Newell, 2013). In other words, DL focuses more on emulating a random and large as possible variety of movement patterns (also going beyond current task goals), while NLP focuses more strongly on guiding learners to adapt to specific task and environmental constraints (Gray, 2020; Schollhorn et al., 2012; Ranganathan & Newell, 2013). To make sure, both NLP and DL fundamentally differ in enlarging movement variability during practice, while LP aims to reduce this variability in order to achieve a universal, golden standard. For as far as we are aware, it remains to be seen which of these motor learning methods are more helpful for changing kinematic and kinetic risk factors of non-contact ACL injury during side-step cutting.

The effectiveness of other types of motor learning methods in preventing ACL injury (reduction of ground reaction force and change of joint angles during landing and cutting) has been investigated previously. For example, it has been shown that the use of external instead of internal focus of attention can help prevent ACL injury in basketball and rugby (for overview see Benjaminse et al., 2017; Widenhoefer, Miller, Weigand, Watkins, & Almonroeder, 2019). However, as suggested by Gokeler, Neuhaus, Benjaminse, Grooms, & Baumeister, (2019), new motor learning methods (such as NLP and DL) can also be effective in this regard. DL and NLP are two methods derived from ecological psychology and the dynamic systems approach. Coordination from this combined approach describes the integration of the individual degrees of freedom into functional units (Newell & McDonald, 1994). Functional variability in the movement system is expected to play a role in preventing ACL injury (van Emmerik & van Wegen, 2000). In the context of both performance and acute injury in team sports, a certain level of coordinative variability may be desirable to evade an opponent and distribute joint loading (Weir, van Emmerik, Jewell, & Hamill, 2019). In the present study, we examine if DL and NLP, which both aim to increase movement variability during, can reduce kinetic and kinematic risk factors during exercise compared to more traditional LP methods.

The purpose of this study was to examine the effect of motor learning method (LP, NLP and DL) on changes in kinetic and kinematic factors related to non-contact ACL injuries during expected sidestep cutting. We hypothesized that in athletes who trained using according to NLP or DL methods, the knee, trunk and hip flexion would increase more and vertical ground reaction force (VGRF) would decrease more, compared with athletes who trained using the LP method. We believe that our findings potentially provide valuable insights into how using the most appropriate motor learning method may enhance the effectiveness of motor learning programs designed for ACL injury prevention.

2.0 Methods

A randomized controlled trial design was used to complete the objective of this study. Upon enrollment, participants were randomly allocated to one of three groups. Participants in all of three groups completed testing before (pretest) and after (post testing) completion of a 12-week soccer training program using LP, NLP or DL method. During testing sessions participants completed running and anticipated sidestep cutting.

2.1 Participants

A total of 66 collegiate males participated in this study (22 participants per group). The rationale for 66 participants was to allow potential 11 vs. 11 game formats as part of the program when required. Participation was voluntarily. All participants were beginners in soccer, and their skill level was determined in a soccer game based on expert opinion (someone who has a history of playing soccer and coaching at different levels). Participants had to be: (1) ≥18 years old, and have (2) no experience in soccer or sports similar to soccer such as futsal, (3) no medical problems that can affect the results, such as restricted vision, (4) no history of ACL injury and were (5) no physical education students. The participants' age, body mass, and height, are provided in Table 1. One-way ANOVAs did not reveal differences between groups in terms of their demographics (see Table 1). The study was approved by the Institutional Review Board, and participants were informed of the benefits and risks of the investigation before signing an institutionally approved informed consent document to participate in the study. All athletes were aged 18 years or older, so parental consent was not required.

<<Insert Table 1 near here>>

2.2 Procedure

Prior to any testing, the pre-designed training environment and test procedure were explained to all participants and were shown to the participants. For the test procedure participants had to run a 5 m path, then rapidly change the direction of their path by 45 degrees with the dominant leg (leg which participant would have preferred to perform the cutting on), and continue running for another 5 m (Benjaminse et al., 2017; Anne Benjaminse, Welling, Otten, & Gokeler, 2018). Kinematics were recorded using a 10-camera motion capture system sampling at 200 Hz [Motion Analysis (Raptor E), Software=Cortex 7.0, USA], and kinetics using two force plates embedded in the lab floor [AMTI (AccuGait-O, 1000 HZ), USA] sampling at 1000 Hz. For further guidance to the participants, all paths were marked with white lines (against the yellow ground color). Approach speed was set between 4.5 and 5.5 m/s based on recommendations from previous research (Vanrenterghem, Venables, Pataky, & Robinson, 2012). To control the participants speed, one person measured the speed of an approach with a chronometer recording time over a 5 m approach distance and thus, ensuring the trial had an average approach speed of between 4.5 to 5.5 m/s; otherwise, the participant was allowed another attempt. In addition, approach speed was checked retrospectively, through calculating the speed of the PSIS markers in the anterior-posterior direction. If the average speed was between 4.5 and 5.5 m/s, the trial was deemed acceptable and retained for further analysis.

Participants had 21 reflective markers of 14 mm in diameter placed according to the Vicon Plug-in-Gait marker set and model (Benjaminse et al., 2017; Anne Benjaminse et al., 2018). This was followed by a static calibration. Participants wore only swimming trunks to enable bony landmarks to be seen and enable accurate marker placement. All participants conducted a 15-minute warm up and were allowed practice trials of the side-step cutting task as part of the warm-up. For each participant three (Franklyn-Miller et al., 2017) correct trials (speed within the specified range, turning angle approximately 45 degrees, and continued running 5 m after changing direction) were recorded. Pre- and post-tests were performed in a laboratory under similar conditions before and after the intervention. The investigators who completed pre- and post-testing were blinded to the athletes’ group allocation.

2.3 Interventions

All interventions lasted 12 weeks with two one and a half hour sessions each week. Overall, one session consisted of 15 minutes of warm-up, 45 minutes of practice and half an hour of play, which included cooling off at the end. The LP group practiced on Saturdays and Mondays, the DL group trained on Sundays and Tuesdays and the NLP group on Wednesdays and Fridays to avoid contamination between groups. Each group was trained by a separate instructor, and all three of them had a master's degree in physical education. They had at least five years of coaching experience in soccer schools and sports teams. Each instructor was experienced with the selected training method. If due to circumstances more than two persons of a group were absent, the session was cancelled and postponed to the next day in another stadium. The soccer skills practiced included mostly shooting, dribbling, receiving, crossing, defending, and passing. For each skill, the instructor tried to consider a practice form that involved some cutting aspect. For example, in a shooting drill, the player ran in a straight path, then redirected through a side-step cut before shooting, or in a receiving drill, a player moved from the left or right via a side-step cut after receiving the ball.

LP

In this method, the instructor first introduced the skill (such as a pass), then he explained that verbally, and in the next stage showed participants the correct way to do that. Participants were then asked to practice the skill, and at each stage with augmented feedback sought to improve the skill. The instructor changed the skill as the group average progressed, and several times demonstrated the correct execution if a participant did not do the desirable movement. In this method, feedback decreased as the participants progressed, and with reaching the optimal pattern, variability and errors reduced (Schmidt et al., 2018). The instructor encouraged the players to practice a skill over a fixed distance for many times. However, he would then allow them to practice the same skill in the same way but from another fixed distance (limited and structured variability, Ranganathan & Newell, 2013).

NLP

In the nonlinear method, the instructor did not verbally provide explicit augmented instructions or feedback regarding an ‘ideal’ movement pattern (the ‘how to do it’). Instead,he provided ‘broad statements’ that acted as boundary constraints on the skills practiced by the learners. So, the instructor did not address specific movement components in terms of how to coordinate limb segments and joints in achieving the task goals, but manipulated tasks and environmental constraints to encourage the player to search and find their own solutions for reaching the goal. By repeatedly promoting search under similar constraints, variable solutions are explored, allowing players their individual adaptive solution(s) (Moy, Renshaw, & Davids, 2016; Ranganathan & Newell, 2013; Renshaw, Chow, Davids, & Button, 2015). When the participants were able to achieve the desired outcome, the environment and/or task constraints were further manipulated to provide a new challenge (Chow et al., 2007; Moy et al., 2016; Moy, Renshaw, Davids, & Brymer, 2019; Renshaw, Oldham, & Bawden, 2012; Renshaw et al., 2015). In this group, the instructor considered the skills of each of the participants (not based on group average) and adjusted the task and environment constraints according to their skill level and individual characteristics to help them learn the skill. However, the instructor was not allowed to tell the participant how to perform the skill.

DL

In this method, participants were never meant to perform the same pattern, hence instructions and exercises were never identical nor was feedback about an executed movement pattern provided. The required movement patterns were verbally instructed (as in Santos et al., 2018). Thus, every trial came together with a new prescription of how to move to achieve the task goal. In the DL, the instructor determined how to kick. For example, he would say to the participant, "You have to kick with the inside of the foot" (this move was only demonstrated once and not repeated). The participant did not receive corrective feedback about the executed movement pattern. In this method to benefit from the variability, different ways of training, such as kicking with the inside of the foot, outside of the foot, or other techniques, from different distances was practiced in an random or unstructured way (Ranganathan & Newell, 2013). More details about the characteristics and the differences between methods LP, NLP and DL can be found in Table 2.

Insert Table 2 near here

2.4 Data processing

All data from the test measures were analyzed in MATLAB (Mathworks Matlab R2019b v9.7.0.1190202). Marker and force data from the side-step cutting trials were filtered using a fourth order, zero-lag, and recursive Butterworth filter. A cutoff frequency of 15 Hz was used for the marker data, and a cutoff frequency of 50 Hz was used for the force plate data (as. Ghanati, Letafatkar, Almonroeder, & Rabiei, 2020). A trunk and lower extremity 6 degrees of freedom kinematic model was created for each participant from a standing trial. This model consisted of a trunk, pelvis, thighs, shanks and feet and used to quantify the motion of the trunk, and at the hip, knee and ankle using the Cardan angle sequence (Grood & Suntay, 1983). The model utilized a CODA pelvis orientation to define the location of the hip joint center (Bell, Brand, & Pedersen, 1989). Knee and ankle joint centers were defined as the mid-point of the line between lateral and medial markers. Joint moments were determined using an inverse dynamics approach (Winter, 2009) and reported as external moments. GRFs and joint moments were normalized to body weight.

All dependent variables were determined at the instant of the peak impact of the vertical component of the GRF of the plant foot during side-step cutting maneuver. This point in time was used to evaluate the angles and moments because it represented the greatest point of impact loading. Kinematic variables determined at this moment were trunk flexion angle (TFA), hip flexion angle (HFA), knee flexion angle (KFA), knee valgus angle (KVA), ankle dorsiflexion angle (ADA), hip ROM (HROM), knee ROM (KROM), ankle ROM (AROM) [range of motion from initial contact to the point of peak vGRF], peak hip flexion (HFR), and peak knee flexion (KFR). Kinetic dependent variables determined were peak VGRF and knee extension/flexion moment (KEFM), knee valgus moment (KVM), and ankle dorsiflexion moment (ADM) at the point of peak impact vertical GRF.

2.5 Statistical analysis

Data were analyzed in SPSS for Windows version 24 (Chicago, Ill). Normality of each kinematic and kinetic variable was assessed using visual inspection of histograms in conjunction with a Kolmogorov-Smirnov test ($P > 0.05$). For those variables showing non-normal distributions Johnson-transformation was applied. Raw continuous variables that were normally distributed were reported as means and standard deviations (SDs), whereas normalized continuous variables (not normally distributed) were reported as median and interquartile range. One-way analysis of covariance (ANCOVA) with a between-factor of group (LP, NLP, and DL), and pretest scores included as a covariate, was used to determine if there were group differences in the dependent variables at post testing. This analysis approach (i.e., posttest performance as the outcome with baseline performance as a covariate) allowed us to compare post testing outcomes while accounting for potential baseline group differences (Van Breukelen, 2006). An alpha of 0.05 was used for all statistical tests. For effects size, partial eta squared are reported, with 0.14, 0.06 and 0.01 referring to large, moderate and small effect size, respectively. Post hoc comparisons were made using LSD tests.

3.0 Results

All participants who completed the pre-test also returned for post testing. The participants' kinetic and kinematic scores are presented in Table 3. The results for the ANCOVA tests for kinematic, and kinetic variables are reported in Table 4.

<<Insert Tables 3 and 4 near here>>

Post hoc tests showed significant difference between groups NLP and LP, as well as, between groups DL and LP ($p < 0.05$). That is, for all the kinetic and kinematic variables, both NLP and DL groups performed better than the LP group (i.e., more flexion at joint angles, increase moments and less vGRF). As well as, a significant difference was observed between NLP and DL groups in most kinematic variables (i.e., TFA, HFA, KFA, KVA, ADA, HROM, KROM, AROM, HFR, KFR) ($p's < 0.05$). However, for the VGRF ($p = 0.44$), KFEM ($p = 0.19$), KVM ($p = 0.17$), and ADM ($p = 0.09$) no significant differences between NLP and DL groups were found. In sum, the NLP group showed better performance for most of the kinetic and kinematic variables compared to the two groups, while DL group in turn showed better performance than the LP group (see Figure 1, 2, and 3).

<<Insert Figure 1, 2, and 3 near here>>

4.0 Discussion

The purpose of this study was to investigate the effects of LP, NLP and DL on kinetic and kinematic variables related to ACL injury risk during anticipated sidestep cutting. Our main hypothesis was confirmed: In the NLP and DL methods, the joint angles increased more and the

VGRF decreased more than in the LP method. This shows the advantage of enhancing variability rather than reducing variability during training.

Accordingly, in our study NLP and DL methods were proven to be more effective methods in modifying risk factors of ACL injury, that is, joint flexion angles were increased more and vGRF was reduced more. When the amount of flexion in joints increases, the flexibility and adaptability in the joint increases, and this reduces the force applied to ligaments by the muscles (Benjaminse et al., 2017; Crenshaw et al., 2000; Hewett et al., 2005; Onate, Guskiewicz, & Sullivan, 2001). Importantly, the NLP group also appears to perform better than the DL group, although the VGRF and moments (KFEM, KVM, and ADM) did not differ significantly (yet, numerically also here an advantage for the NLP method might be seen). Therefore, NLP may be the more effective strategy for modifying risk factors of ACL injury than DL, while both are clearly more effective than LP in this regard.

In the present study, LP was identified as the weakest method in the prevention of ACL injury. We argue this is due to the reduced execution variability during training associated this method (Bartlett et al., 2007; Bernstein, 1967; Orth, van der Kamp, Memmert, & Savelsbergh, 2017; Ranganathan & Newell, 2013). In fact, our findings suggests that variability in practice best allows the person to search and choose a more appropriate solution in accordance with the constraints of the task and the environment, increasing the person's adaptability to the environment (Dhawale et al., 2017; Newell & McDonald, 1994; Vereijken, Emmerik, Whiting, & Newell, 1992). Increased variability during practice is thus considered functional. It provides the performer with a more degenerate movement coordination repertoire, increasing adaptiveness to the dynamic environment and presumably reducing injury risk (Bartlett et al., 2007; Gokeler, Benjaminse, Seil, Kerkhoffs, & Verhagen, 2018; Gokeler et al., 2019).

One may derive from the present results that the NLP may be the best of three methods (LP, NLP and DL) for reducing key risk factors for ACL injury. Yet, further research is needed to statistically verify this especially for the vertical ground reaction force and moments (KFEM, KVM, and ADM). Nonetheless, this advantage for NLP relative to DL, suggest that a factor additional to merely increasing the variability is effective in modifying risk factors of ACL injury. This factor may be the active, self-regulated exploration or search that is especially promoted in NLP method, unlike DL where variability seems more externally imposed. Ranganathan & Newell, (2013) argue that intrinsic variability (finding solutions to constraints of the environment and the task), which is a feature of the NLP method, is more effective in exploration and reinforcement learning than externally imposed variability (i.e., prescribed instructions and feedback), which is a feature of the DL method. Also, manipulation in NLP allows the assessment of another component of motor learning, namely, flexibility. In other words, participants can quickly find alternative solutions when a well-practiced solution is no longer feasible. So, self-regulated exploring solutions to perform a task could have two effects on learning: 1) it can lead to the emergence of a more individual adaptive solutions for a task because there is a search or exploration of the task solution space; and 2) it can also improve degeneracy, that is, the ability to instantaneously adapt in multiple ways to the local dynamics. In prescribed imposed exploration of the solution space, this adaptation and degeneracy to the task constraints gets less prioritized, since attention is directed toward emulating the prescribed movement pattern or solution also beyond the task space. This flexibility makes a person more apt or prepared to adapt to (unexpectedly) changing conditions and constraints, and to move with greater skill and fluency. This will likely also protect the individual against situations in which high stresses are placed on the musculoskeletal system from having to achieve the desirable movements forcefully, eventually reducing for example the risk of a non-contact ACL injury.

The strengths of this study were the use of three training methods, the observation of a carefully standardized cutting task in a laboratory environment, and a soccer-related intervention in the participants' natural environment. An important limitation of the present study was that only male novice participants could be included. As a result, we have to be careful generalize our findings to other groups. In particular, female have been shown to respond differently to varying types of motor learning strategies to prevent ACL (Benjaminse et al., 2017). Also, further research is needed to reveal whether our findings can be extrapolated to other kinematic and kinetic risk factors of ACL injury in other tasks, such as landing.

5.0 Conclusions

The results of this study highlight the role that training induced variability can play in soccer training for prevention of ACL injuries. Both NLP and DL training methods resulted in greater increase in knee flexion and greater reduction in VGRF than a LP training method. Additionally, the current study is suggestive in participants benefitting most from the NLP method. Tailoring training environments based on careful manipulation of constraints that maximally exploit movement variability and exploration, instead of direct and prescriptive instructions, are advised for reducing non-contact ACL injury risk.

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Table 1. Demographic information of participants

	All N=66 mean±SD	Linear (group 1) N=22 mean±SD	Nonlinear (group 2) N=22 mean±SD	Differential (group 3) N=22 mean±SD	F	P
Age (years)	27.5±2.7	26.9±2.7	27.7±2.6	27.9±2.8	0.9	0.41
mass (kg)	78.2±4.6	78.9±4.8	77.8±4.5	77.9±4.6	041	0.66
Height (cm)	180.9±4.9	181.1±5.5	180.3±4.8	180.4±4.4	0.18	0.83
BMI (kg/m2)	23.7±0.4	23.1±0.6	23.9±0.4	23.9±0.4	0.13	0.87

Table 2. Key characteristics of the different motor learning strategies.

Teaching Rules	LP	NLP	DL
Target	The task goal was explicitly defined and it was important to achieve it.	The task goal was explicitly and it was important to achieve it.	Task goal may be absent, but how the action was executed was important.
Pattern	There was a prescribed ideal pattern and the participants were attending to it.	There was no prescribed ideal pattern. Participants produced a pattern based on their own characteristics, and tasks and environmental constraints.	There were many prescribed patterns, and the participants were attending to it.
Description	The task goal and movement pattern were fully described.	The task goal was identified but the movement patterns were not described.	Each movement pattern and task goal was described.
Prescription	Prescription was encouraged.	Prescription was not allowed.	Prescription was encouraged.
Repeat	Repetition was encouraged.	Repetition was allowed.	Repetition was not allowed.

Variability	Minimized with modest structured variability (e.g., changing distance) being allowed, but participant's attention was toward prescribed movement.	Semi-structured variability was encouraged using manipulation of task and environment constraints. Participant's attention was directed to search adaptive solutions.	Random variability was encouraged by prescribing different movement patterns and also manipulations of task and environmental constraints was allowed. Participants attended to prescribed motor pattern.
Feedback	Feedback on the movement pattern was encouraged.	Feedback on the movement pattern was not allowed.	Feedback on the movement pattern was not allowed.
Instructions	Instructions were encouraged to convey the ideal movement pattern.	Instructions were allowed to manipulate task constraints.	Instructions were encouraged to prescribe always differing movement patterns.

Table 3. The participants' kinetic and kinematic scores

		All N=66 mean±SD	LP N=22 mean±SD	NLP N=22 mean±SD	DL N=22 mean±SD
TFA$^{a(°)}$	Pre-test	0.16±1.58	0.16±1.71	0.21±1.76	0.12±1.00
	Post-test	0.14±1.36	-1.17±1.45	0.73±1.62	0.26±0.69
HFA$^{a(°)}$	Pre-test	-0.24±1.50	0.01±1.78	-0.10±1.44	-0.46±1.03
	Post-test	-0.13±1.36	-0.83±1.51	0.63±1.24	-0.22±0.85
KFA$^{a(°)}$	Pre-test	38.37±4.33	38.68±4.64	37.81±4.62	38.60±3.83
	Post-test	48.07±6.24	43.90±4.44	52.31±5.93	47.99±5.33
KVA $^{(°)}$	Pre-test	-2.09±0.71	-2.06±0.64	-2.17±0.82	-2.04±0.68
	Post-test	-4.96±1.47	-4.02±1.18	-5.91±1.34	-4.96±1.30
ADA^{a} $^{(°)}$	Pre-test	-0.07±1.31	0.10±1.38	-0.09±1.39	-0.09±1.49
	Post-test	0.04±1.37	-0.74±0.70	0.69±1.23	0.09±0.96
HROM $^{a(°)}$	Pre-test	-0.02±1.39	-0.27±1.41	0.19±1.29	-0.07±1.43
	Post-test	0.01±1.50	-0.81±1.27	0.97±1.15	0.03±1.04
KROM $^{a(°)}$	Pre-test	0.05±1.42	0.08±1.30	-0.008±1.35	0.22±1.48
	Post-test	-0.13±1.37	-0.64±0.67	0.94±1.08	-0.13±1.21
AROM $^{a(°)}$	Pre-test	-0.03±1.63	0.24±1.86	-0.08±1.60	-0.03±1.31
	Post-test	-0.05±1.42	-0.72±1.28	0.76±0.99	-0.06±0.87
HFR ^{a} $^{(°)}$	Pre-test	0.10±1.32	-0.09±1.21	0.44±1.49	0.007±1.34
	Post-test	-0.05±1.33	-0.98±1.05	0.66±0.95	0.07±1.09

KFR$^{a(°)}$	Pre-test	-0.07±1.41	-0.04±1.34	-0.28±1.46	0.15±1.39
	Post-test	-0.01±1.45	-0.65±1.26	0.14±1.08	0.13±1.45
VGRF ^{a}	Pre-test	0.15±1.42	-0.43±1.50	0.31±1.33	0.15±1.38
	Post-test	-0.11±1.62	0.94±1.30	-0.33±1.44	-0.26±0.74
KEFM^{a}	Pre-test	-0.06±1.36	-0.03±1.71	0.29±1.51	-0.26±1.25
	Post-test	0.08±1.34	-0.67±0.98	0.65±0.97	0.08±1.45
KVM ^{a}	Pre-test	0.16±1.34	0.05±1.77	0.006±1.35	0.21±1.42
	Post-test	0.14±1.53	-0.72±1.52	0.72±1.84	0.21±1.34
ADM^{a}	Pre-test	0.09±1.32	0.24±1.24	0.09±1.23	-0.23±1.38
	Post-test	-0.21±1.32	-0.44±1.13	0.69±1.51	-0.09±1.05

a=Outcome normalized through Johnson transformation and expressed in Median ± interquartile range.

Table 4. ANCOVA test results for each of the kinetic and kinematic variables

variables	F*	DF*	P*	Partial Eta Squared
trunk flection angle (TFA)	41.38	(2,62)	<0.001	0.572
hip flexion angle (HFA)	48.82	(2,62)	<0.001	0.612
knee flexion angle (KFA)	69.96	(2,62)	<0.001	0.693
knee valgus angle (KVA)	25.87	(2,62)	<0.001	0.455
ankle dorsiflexion angle (ADA)	32.17	(2,62)	<0.001	0.509
hip ROM (HROM)	40.98	(2,62)	<0.001	0.569
knee ROM (KROM)	19.43	(2,62)	<0.001	0.385
ankle ROM (AROM)	25.10	(2,62)	<0.001	0.447
Peak hip flection (HFR)	39.89	(2,62)	<0.001	0.563

Peak knee flexion (KFR)	25.87	(2,62)	<0.001	0.455
VGRF	21.10	(2,62)	<0.001	0.405
knee extension/ flexion moment (KEFM)	22.08	(2,62)	<0.001	0.416
knee valgus moment (KVM)	21.64	(2,62)	<0.001	0.411
ankle dorsiflexion moment (ADM)	30.93	(2,62)	<0.001	0.499

** F= ANCOVA value, P=P value, DF=Degree of freedman*

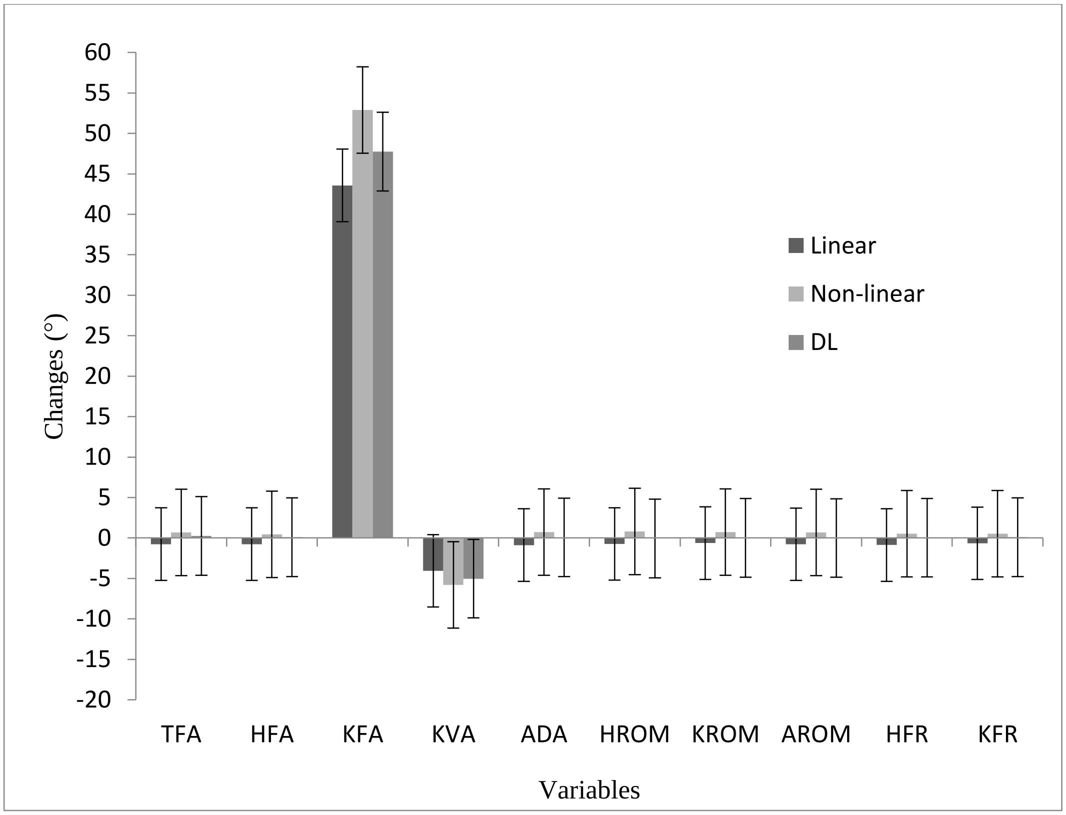

Figure 1, comparing the estimated marginal means for trunk flection angle (TFA), hip flexion angle (HFA), knee flexion angle (KFA), knee valgus angle (KVA), ankle dorsiflexion angle (ADA), hip ROM (HROM), knee ROM (KROM), ankle ROM (AROM), peak hip flection (HFR), peak knee flexion (KFR)in all training methods.

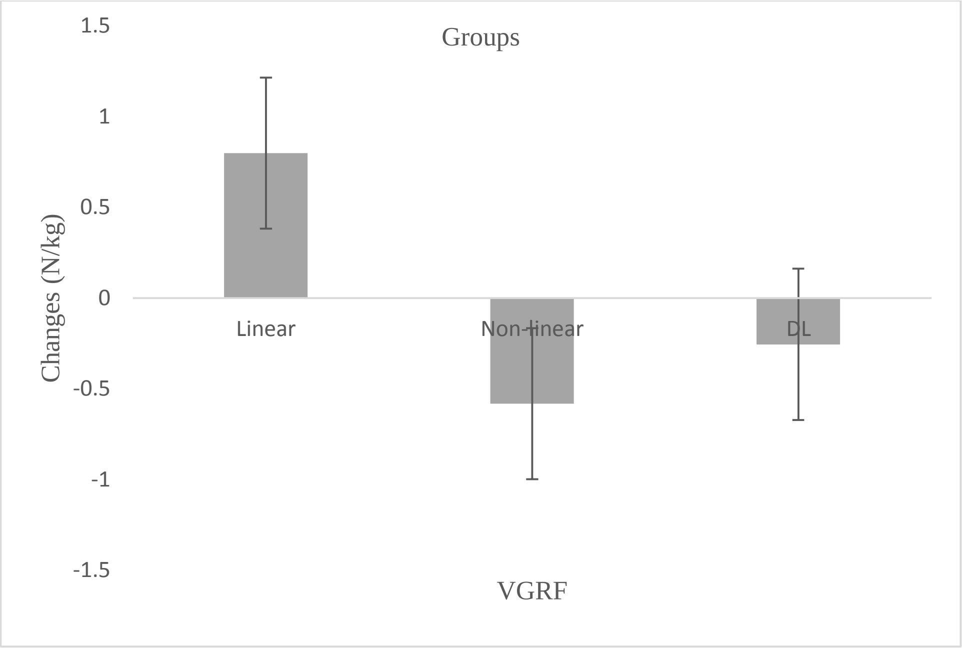

Figure 2, comparing the estimated marginal means for vertical ground reaction force (VGRF).

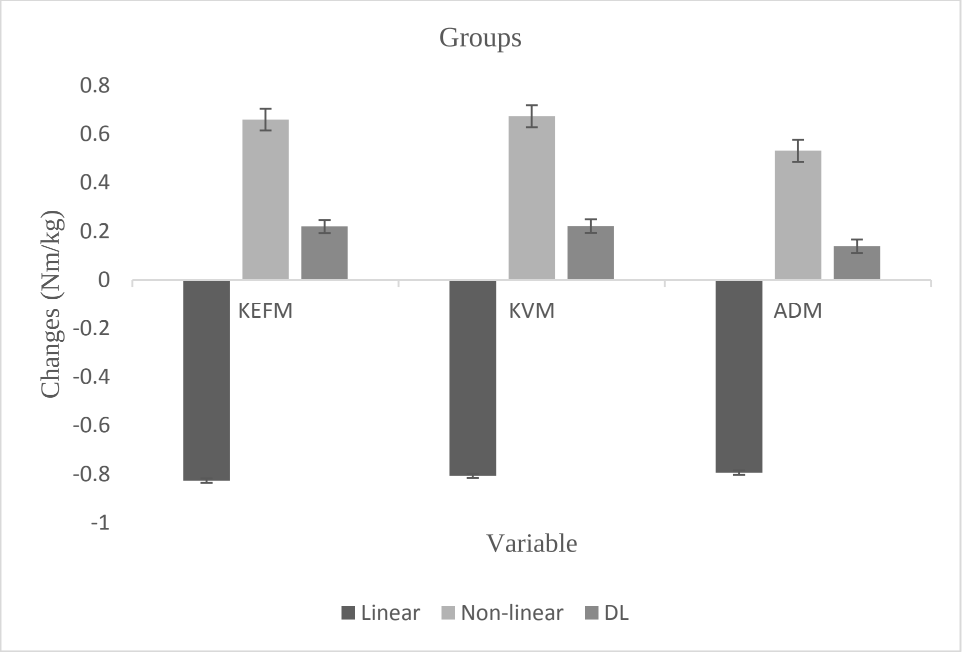

Figure 3, comparing the estimated marginal means for Knee extension/ flexion moment (KEFM), knee valgus moment (KVM), ankle dorsiflexion moment (ADM) in all training methods.

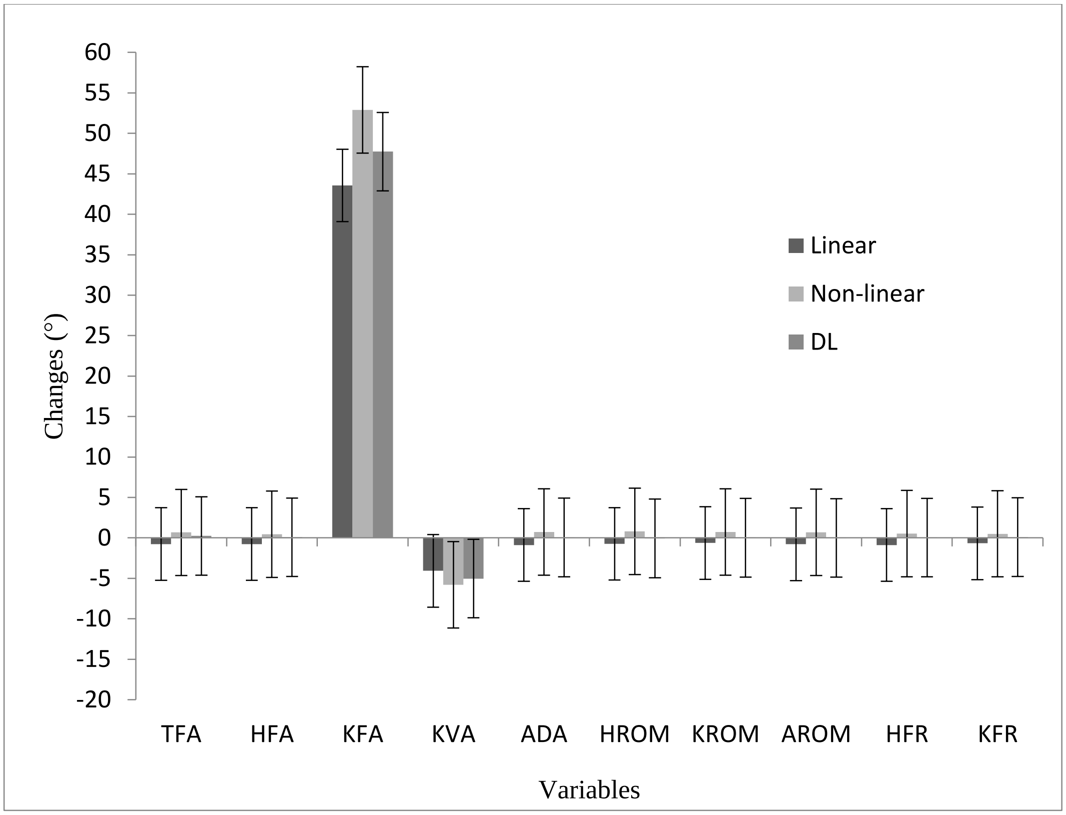

Figure 1, comparing the estimated marginal means for trunk flection angle (TFA), hip flexion angle (HFA), knee flexion angle (KFA), knee valgus angle (KVA), ankle dorsiflexion angle (ADA), hip ROM (HROM), knee ROM (KROM), ankle ROM (AROM), peak hip flection (HFR), peak knee flexion (KFR)in all training methods.

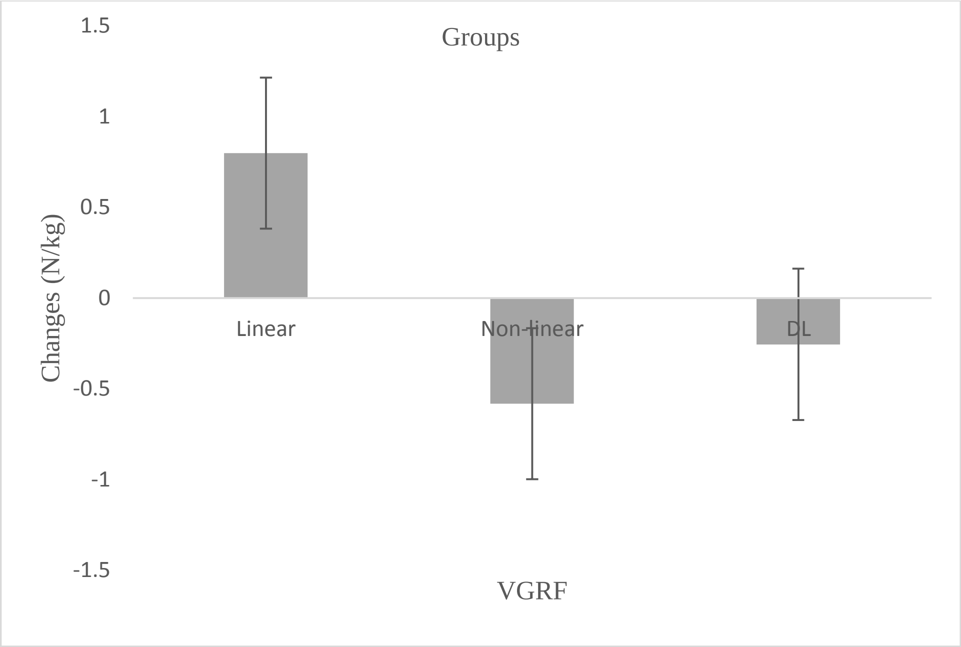

Figure 2, comparing the estimated marginal means for vertical ground reaction force (VGRF).

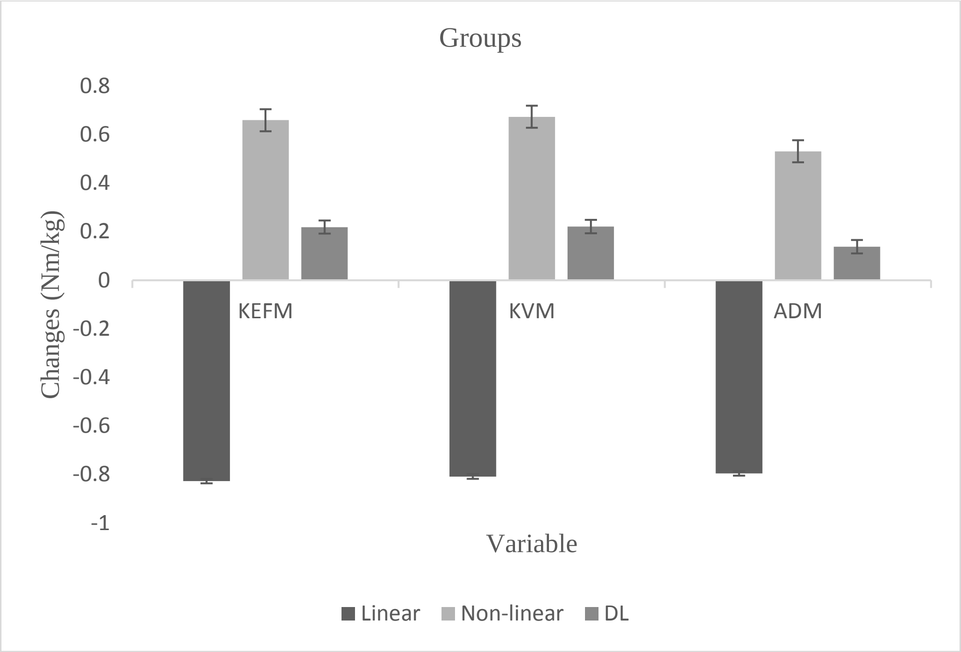

Figure 3, comparing the estimated marginal means for Knee extension/ flexion moment (KEFM), knee valgus moment (KVM), ankle dorsiflexion moment (ADM) in all training methods.

Table 1. Demographic information of participants

	All N=66 mean±SD	Linear (group 1) N=22 mean±SD	Nonlinear (group 2) N=22 mean±SD	Differential (group 3) N=22 mean±SD	F	P
Age (years)	27.5±2.7	26.9±2.7	27.7±2.6	27.9±2.8	0.9	0.41
mass (kg)	78.2±4.6	78.9±4.8	77.8±4.5	77.9±4.6	041	0.66
Height (cm)	180.9±4.9	181.1±5.5	180.3±4.8	180.4±4.4	0.18	0.83
BMI (kg/m2)	23.7±0.4	23.1±0.6	23.9±0.4	23.9±0.4	0.13	0.87

Table 2. Key characteristics of the different motor learning strategies.

Teaching Rules	LP	NLP	DL
Target	The task goal was clear and it was important to achieve it.	The task goal was clear and it was important to achieve it.	Task goal may be absent, but how action was executed was important.
Pattern	There was a prescribed ideal pattern and the participants were attending to it.	There was no prescribed ideal pattern. Participants produced a pattern based on their own characteristics, and tasks and environmental constraints.	There were many prescribed patterns, and the participants were attending to it.
Description	The task goal and movement pattern were fully described.	The task goal was identified but the movement patterns were not described.	Each movement pattern and task goal were described.
Prescription	Prescription was encouraged.	Prescription was not allowed.	Prescription was encouraged.
Repeat	Repetition was encouraged.	Repetition was allowed.	Repetition was not allowed.
Variability	Modest structured variability (e.g., changing distance) was allowed, but participant's attention was toward prescribed movement.	Unstructured variability was encouraged using manipulation of task and environment constraints. Participant's attention was directed to discover adaptive solutions.	Unstructured variability was encouraged by prescribing different movement patterns and also manipulations of task and environmental constraints was allowed. Participants attended to prescribed motor pattern.
Feedback	Feedback was encouraged.	Feedback was not allowed.	Feedback was not allowed.
Instructions	Instructions were encouraged (to convey the ideal pattern).	Instructions were allowed (to manipulate task constraints).	Instructions were encouraged (to prescribe always differing movement patterns).

Table 3. The participants' kinetic and kinematic scores

		All	LP	NLP	DL
		N=66	N=22	N=22	N=22
		mean±SD	mean±SD	mean±SD	mean±SD
TFA[a](°)	Pre-test	0.16±1.58	0.16±1.71	0.21±1.76	0.12±1.00
	Post-test	0.14±1.36	-1.17±1.45	0.73±1.62	0.26±0.69
HFA[a](°)	Pre-test	-0.24±1.50	0.01±1.78	-0.10±1.44	-0.46±1.03
	Post-test	-0.13±1.36	-0.83±1.51	0.63±1.24	-0.22±0.85
KFA[a](°)	Pre-test	38.37±4.33	38.68±4.64	37.81±4.62	38.60±3.83
	Post-test	48.07±6.24	43.90±4.44	52.31±5.93	47.99±5.33
KVA (°)	Pre-test	-2.09±0.71	-2.06±0.64	-2.17±0.82	-2.04±0.68
	Post-test	-4.96±1.47	-4.02±1.18	-5.91±1.34	-4.96±1.30
ADA[a](°)	Pre-test	-0.07±1.31	0.10±1.38	-0.09±1.39	-0.09±1.49
	Post-test	0.04±1.37	-0.74±0.70	0.69±1.23	0.09±0.96
HROM [a] (°)	Pre-test	-0.02±1.39	-0.27±1.41	0.19±1.29	-0.07±1.43
	Post-test	0.01±1.50	-0.81±1.27	0.97±1.15	0.03±1.04
KROM [a] (°)	Pre-test	0.05±1.42	0.08±1.30	-0.008±1.35	0.22±1.48
	Post-test	-0.13±1.37	-0.64±0.67	0.94±1.08	-0.13±1.21
AROM [a] (°)	Pre-test	-0.03±1.63	0.24±1.86	-0.08±1.60	-0.03±1.31
	Post-test	-0.05±1.42	-0.72±1.28	0.76±0.99	-0.06±0.87
HFR [a](°)	Pre-test	0.10±1.32	-0.09±1.21	0.44±1.49	0.007±1.34
	Post-test	-0.05±1.33	-0.98±1.05	0.66±0.95	0.07±1.09
KFR[a](°)	Pre-test	-0.07±1.41	-0.04±1.34	-0.28±1.46	0.15±1.39
	Post-test	-0.01±1.45	-0.65±1.26	0.14±1.08	0.13±1.45
VGRF [a]	Pre-test	0.15±1.42	-0.43±1.50	0.31±1.33	0.15±1.38

	Post-test	-0.11±1.62	0.94±1.30	-0.33±1.44	-0.26±0.74
KEFM[a]	Pre-test	-0.06±1.36	-0.03±1.71	0.29±1.51	-0.26±1.25
	Post-test	0.08±1.34	-0.67±0.98	0.65±0.97	0.08±1.45
KVM [a]	Pre-test	0.16±1.34	0.05±1.77	0.006±1.35	0.21±1.42
	Post-test	0.14±1.53	-0.72±1.52	0.72±1.84	0.21±1.34
ADM[a]	Pre-test	0.09±1.32	0.24±1.24	0.09±1.23	-0.23±1.38
	Post-test	-0.21±1.32	-0.44±1.13	0.69±1.51	-0.09±1.05

a=Outcome normalized through Johnson transformation and expressed in Median ± interquartile range.

Table 4. ANCOVA test results for each of the kinetic and kinematic variables

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VGRF	21.10	(2,62)	<0.001	0.405
knee extension/ flexion moment (KEFM)	22.08	(2,62)	<0.001	0.416
knee valgus moment (KVM)	21.64	(2,62)	<0.001	0.411
ankle dorsiflexion moment (ADM)	30.93	(2,62)	<0.001	0.499

* F= ANCOVA value, P=P value, DF=Degree of freedman

AUTHORSHIP STATEMENT

Manuscript title: **Motor learning methods that induce high practice variability reduce kinematic and kinetic risk factors of non-contact ACL injury**

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the human movement science.

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