DO MULTI-PLANAR ACL INJURY RISK VARIABLES RANK INDIVIDUALS MORE CONSISTENTLY ACROSS TASKS THAN UNI-PLANAR VARIABLES?

Raihana Sharir[1], Radin Rafeeuddin[1], Jos Vanrenterghem[2], Mark A. Robinson[1]

**School of Sport and Exercise Sciences, Liverpool John Moores University, UK[1]
Faculty of Kinesiology and Rehabilitation Sciences, KU Leuven, Belgium[2]**

The ACL injury mechanism is multi-planar, yet rarely are multi-planar variables examined in an injury risk context. This study examines if multi-planar variables rank individuals more consistently across multiple tasks than uni-planar variables. Forty-four female athletes performed bilateral drop vertical jumps, single-leg hops, single-leg drop vertical jumps and sidestep tasks on their dominant leg. Uni-planar (KM_{ab}) and multi-planar (KM_{nsag}) variables of the knee were extracted and correlated between tasks. Participants was ranked according to KM_{ab} and KM_{nsag}, and then grouped into quintiles for each task. When variables are consistently ranked across tasks, a movement signature is identified. In total, uni-planar movement signatures were identified more than multi-planar movement signatures. However, both undesirable multi-planar and uni-planar movement signatures were identified in unique participants. Multi-planar and uni-planar variables are both important when screening for undesirable movements.

KEYWORDS: Screening, classification, anterior cruciate ligament, movement signature

INTRODUCTION: The ACL injury mechanism is well documented to involve combinations of undesirable multi-planar forces and motions during dynamic activities (Boden, Dean, Feagin, & Garrett, 2000; Fauno & Wulff Jakobsen, 2006). *In vitro* and *in silico* biomechanical studies have demonstrated that greater magnitudes of ACL strain come from combinations of forces applied to the knee rather than a single uni-planar forces alone (Berns, Hull, & Patterson, 1992; Markolf et al., 1995; Shin, Chaudhari, & Andriacchi, 2011). Consideration of multi-planar forces are clearly important, yet rarely are multi-planar variables examined in an injury risk context.

Previous prospective work on ACL injury has only observed uni-planar variables such as the knee abduction moment, knee abduction angle, vertical ground reaction force, knee flexion angle, hip flexion and knee flexion moment (Hewett et al., 2005; Leppanen, Pasanen, Krosshaug, et al., 2017; Leppanen, Pasanen, Kujala, et al., 2017). However, risk factors found from these studies were independent of each other. As the ACL injury mechanism is well-established to occur in multiple planes and the magnitude of a single load alone leads to lower ACL strain when compared with multi-planar combination of loads (Berns et al., 1992; Markolf et al., 1995), perhaps a more mechanism-informed variable is needed. Altogether, there is reason to believe that multi-planar observations are necessary when trying to investigate the multi-planar individual behaviours that may be associated with increased non-contact ACL injury risk. No *in vivo* biomechanical prospective study has explored multi-planar variables as potential risk factors. Furthermore, if multi-planar variables can be identified across a number of tasks, then these are likely hard-wired behaviours that are task-invariant and representative of an athlete's behaviour, in other words, the athlete's movement signature.

The aim of this study was to determine if the multi-planar loading variables rank individuals more consistently across bilateral drop vertical jumps (BDVJ), single-leg drop vertical jumps (SLDVJ), single-leg hops (SLHOP) and sidestep (SS) tasks than uni-planar loading variable.

METHODS: Forty-four female athletes (mean ± SD: age, 22.1 ± 3.7 years; 64.0 ± 10.6 kg) who regularly participated in highly-dynamic sports participated in this study. After warm-up and familiarisation, participants performed five trials each of BDVJ, SLDVJ, SLHOP and a 45° anticipated SS all on their dominant leg. Motion data were captured at 250 Hz (10 Oqus Cameras and QTM v.2.14 Qualisys AB, Gothenburg, Sweden). Ground reaction forces were

measured by two force platforms sampling at 1500 Hz (Kistler InstrumentsLtd., Winterthur, Switzerland). Forty-four spherical markers were used according to the LJMU Lower Limb and Trunk model (Vanrenterghem, Gormley, Robinson, & Lees, 2010). Static and functional joint trials were collected prior to testing to define functional hip and knee joint centres. Motion data were modelled and analysed using Butterworth filter with 20 Hz cut-off frequency in Visual 3D (v.5.02.30 C-Motion, Germantown, MD, USA) (Bisseling & Hof, 2006; Kristianslund, Krosshaug, & van den Bogert, 2012). Touch-down and take-off from the force platform were identified based on a 20 N threshold.

The uni-planar variable observed in this study was the peak external knee abduction moment (KM_{ab}), which was recorded between the initial contact and take-off. The multi-planar variable considered in this study was a resultant vector of the frontal and transverse plane knee moments, i.e. a non-sagittal plane knee moment vector (KM_{nsag}). Peak resultant vectors for the multi-planar loading were obtained between initial contact and take-off. Mean values for each task were obtained and correlated in task pairs using a Spearman's rank correlation coefficient (ρ) to assess the ranking differences between tasks. Correlation coefficients were rated as very good (0.90-1.00), good (0.70-0.89), moderate (0.40-0.69), poor (0.20-0.39) or very poor (0.00-0.19). Participants' moments were then ranked separately and split into quintiles for each task. The 5th quintile contained the highest moments or a more undesirable rank, while the 1st quintile represented the lowest scores or a more desirable rank. A participant was considered to have a "movement signature" if they had a consistent quintile rank across tasks where all tasks ranked in the same quintile; or 3 tasks ranked in the same quintile with 1 task ranked ± one difference to the majority quintile i.e. 3rd, 3rd, 3rd, 2nd or 3rd, 3rd, 3rd, 4th. If there were more inconsistent quintile rankings across tasks, no movement signature was recorded.

Table 1. The table below illustrates each participant's unique movement signatures and its quintile rank. Different colour blocks represent different movement signature rankings

Participant	KM_{ab}	KM_{nsag}
1	5th (purple)	
2		
3		
4	1st (yellow)	
5		4th (blue)
6		
7		
8	5th (purple)	
9	3rd (teal)	
10	5th (purple)	
11		3rd (teal)
12	3rd (teal)	
13	5th (purple)	
14	4th (blue)	
15		4th (blue)
16	3rd (teal)	
17		
18	1st (yellow)	
19	2nd (green)	
20	3rd (teal)	
21		
22		
23	5th (purple)	
24	1st (yellow)	5th (purple)
25	1st (yellow)	
26		
27		
28		5th (purple)
29		5th (purple)
30	5th (purple)	

* Quintile rank colour

1st	2nd	3rd	4th	5th
Low				High
yellow	green	teal	blue	purple

RESULTS: Overall, moderate correlation was seen for the uni-planar variable (KM_{ab}) (ρ=0.37–0.64) and mostly very poor correlations were observed for multi-planar variables (KM_{nsag}) across tasks (ρ=-0.01–0.55). KM_{ab} were significantly correlated across all tasks pairs however, only the SLDVJ and SLHOP pair were significantly correlated for KM_{nsag}. Out of the total number of participants and variables (n=88), 22 individual movement signatures were identified (Table 1). KM_{ab} (n=16) had more movement signatures than KM_{nsag} (n=6). 21 out of 44 females was identified with at least one movement signature either desirable or undesirable but 12 out of the 21 movement signatures identified were undesirable (4th and 5th quintile). Seven out of sixteen undesirable KM_{ab} and five out of six KM_{nsag} were observed however, none of the participants had a combination of uni-planar and multi-planar undesirable movement signatures.

DISCUSSION: This study aimed to determine if a multi-planar loading variable ranks individuals more consistently than uni-planar loading variables across BDVJ, single-leg drop SLDVJ, SLHOP and SS tasks. KM_{ab} were significantly correlated across all tasks but otherwise at a cohort level, only moderate relationships was seen. KM_{ab} were

consistently rank more than KM_{nsag} therefore indicating the existence of movement signatures.

The KM_{ab} movement signature was identified more than KM_{nsag} movement signatures which could likely be influenced by the magnitude from the frontal or transverse plane moment (Pollard, Sigward, & Powers, 2007) as well as the reliability of the knee abduction moment was questionable (Malfait et al., 2014; Sankey et al., 2015). This means, someone who has a KM_{ab} based movement signature may not necessarily have high frontal or transverse plane moments, therefore would not be identified as having a KM_{nsag} movement signature. These differences may also explain why poor correlation was found between uni-planar and multi-planar variables in the spearman correlation.

More than half (55%) of the total movement signature identified (n=22) were highly ranked therefore, this means that when individuals are consistently ranked across tasks, there is a 1 in 2 chance that they would have an undesirable behaviour. This therefore justifies the capability of the movement signature to perceive undesirable behaviour. The highly ranked (undesirable) uni-planar and multi-planar movement signatures were identified in different participants. This shows that KM_{ab} alone is unlikely to capture all individuals with undesirable movement signatures, therefore both KM_{ab} and KM_{nsag} can contribute to identifying individuals at risk. Due to the low injury rates and lack of predicting power of existing individual risk factors (Bahr, 2016), identifying at risk individuals remains a challenge. Observing both uni-planar and multi-planar movement signatures may provide a better tool for screening as it appears to capture global behaviour across varying tasks more effectively in addition of taking the multi-planar aspect of ACL injury into account. As screening individuals using multi-planar variable is a new concept of screening at-risk individuals its value should be tested in a prospective study.

CONCLUSION: Distinct differences in the frequency of uni-planar versus multi-planar knee movement signatures were observed in the female cohort studied. Uni-planar knee movement signatures were identified more than the multi-planar movement signature and were independent of each other. Seven out of sixteen uni-planar movement signatures and five out of six multi-planar movement signature identified were undesirable. Therefore, both uni-planar and multi-planar variables should be considered when screening for injury as both of these variables are of importance in identifying at-risk movements. The majority of the total number of movement signatures identified as highly ranked demonstrates that task-invariant movement signatures better inform undesirable (at-risk) behaviours. The findings of this may result in better injury screening through inclusion of the multi-planar commonalities that exist across commonly employed knee injury screening tasks.

REFERENCES
Bahr, R. (2016). Why screening tests to predict injury do not work-and probably never will...: a critical review. *Br J Sports Med, 50*(13), 776-780. doi:10.1136/bjsports-2016-096256
Berns, G. S., Hull, M. L., & Patterson, H. A. (1992). Strain in the anteromedial bundle of the anterior cruciate ligament under combination loading. *J Orthop Res, 10*(2), 167-176. doi:10.1002/jor.1100100203
Bisseling, R. W., & Hof, A. L. (2006). Handling of impact forces in inverse dynamics. *J Biomech, 39*(13), 2438-2444. doi:10.1016/j.jbiomech.2005.07.021
Boden, B. P., Dean, G. S., Feagin, J. A., Jr., & Garrett, W. E., Jr. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics, 23*(6), 573-578.
Fauno, P., & Wulff Jakobsen, B. (2006). Mechanism of anterior cruciate ligament injuries in soccer. *Int J Sports Med, 27*(1), 75-79. doi:10.1055/s-2005-837485
Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Jr., Colosimo, A. J., McLean, S. G., . . . Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med, 33*(4), 492-501. doi:10.1177/0363546504269591

Kristianslund, E., Krosshaug, T., & van den Bogert, A. J. (2012). Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention. *J Biomech, 45*(4), 666-671. doi:10.1016/j.jbiomech.2011.12.011

Leppanen, M., Pasanen, K., Krosshaug, T., Kannus, P., Vasankari, T., Kujala, U. M., . . . Parkkari, J. (2017). Sagittal Plane Hip, Knee, and Ankle Biomechanics and the Risk of Anterior Cruciate Ligament Injury: A Prospective Study. *Orthop J Sports Med, 5*(12), 2325967117745487. doi:10.1177/2325967117745487

Leppanen, M., Pasanen, K., Kujala, U. M., Vasankari, T., Kannus, P., Ayramo, S., . . . Parkkari, J. (2017). Stiff Landings Are Associated With Increased ACL Injury Risk in Young Female Basketball and Floorball Players. *Am J Sports Med, 45*(2), 386-393. doi:10.1177/0363546516665810

Malfait, B., Sankey, S., Firhad Raja Azidin, R. M., Deschamps, K., Vanrenterghem, J., Robinson, M. A., . . . Verschueren, S. (2014). How reliable are lower-limb kinematics and kinetics during a drop vertical jump? *Med Sci Sports Exerc, 46*(4), 678-685. doi:10.1249/mss.0000000000000170

Markolf, K. L., Burchfield, D. M., Shapiro, M. M., Shepard, M. F., Finerman, G. A., & Slauterbeck, J. L. (1995). Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res, 13*(6), 930-935. doi:10.1002/jor.1100130618

Pollard, C. D., Sigward, S. M., & Powers, C. M. (2007). Gender differences in hip joint kinematics and kinetics during side-step cutting maneuver. *Clin J Sport Med, 17*(1), 38-42. doi:10.1097/JSM.0b013e3180305de8

Sankey, S. P., Raja Azidin, R. M., Robinson, M. A., Malfait, B., Deschamps, K., Verschueren, S., . . . Vanrenterghem, J. (2015). How reliable are knee kinematics and kinetics during side-cutting manoeuvres? *Gait Posture, 41*(4), 905-911. doi:10.1016/j.gaitpost.2015.03.014

Shin, C. S., Chaudhari, A. M., & Andriacchi, T. P. (2011). Valgus plus internal rotation moments increase anterior cruciate ligament strain more than either alone. *Med Sci Sports Exerc, 43*(8), 1484-1491. doi:10.1249/MSS.0b013e31820f8395

Vanrenterghem, J., Gormley, D., Robinson, M., & Lees, A. (2010). Solutions for representing the whole-body centre of mass in side cutting manoeuvres based on data that is typically available for lower limb kinematics. *Gait Posture, 31*(4), 517-521. doi:10.1016/j.gaitpost.2010.02.014