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Biomechanical Associates of Performance and Knee Joint Loads During an 70-90° Cutting Maneuver in Sub-Elite Soccer Players

--Manuscript Draft--

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Corresponding Author:	Alistair James McBurnie, BSc (Hons) Manchester United F.C. Manchester, Greater Manchester UNITED KINGDOM
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Manchester United F.C.
Corresponding Author's Secondary Institution:	
First Author:	Alistair James McBurnie, BSc (Hons)
First Author Secondary Information:	
Order of Authors:	Alistair James McBurnie, BSc (Hons)
	Thomas Dos'Santos, MSc*D
	Paul A Jones, PhD
Order of Authors Secondary Information:	
Manuscript Region of Origin:	UNITED KINGDOM
Abstract:	The aim of this study was to explore the 'performance-injury risk' conflict during cutting, by examining whole-body joint kinematics and kinetics that are responsible for faster change of direction (COD) performance of a cutting task in soccer players, and to determine whether these factors relate to peak external multi-planar knee moments.34 male soccer players (age: 20 ± 3.2 yrs; mass: 73.5 ± 9.2 kg; height: 1.77 ± 0.06 m) were recruited to investigate the relationships between COD kinetics and kinematics with performance and multi-planar knee joint moments during cutting. Three-dimensional motion data using 10 Qualisys Oqus 7 infrared cameras (240 Hz) and ground reaction force (GRF) data from two AMTI force platforms (1200 Hz) were collected to analyze the penultimate (PFC) and final (FFC) foot contacts. Pearson's or Spearman's correlations coefficients revealed performance time (PT), peak external knee abduction moment (KAM) and peak external knee rotation moment (KRM) were all significantly related ($P < 0.05$) to horizontal approach velocity (PT: ρ = - 0.579; peak KAM: ρ = 0.414; peak KRM: R = - 0.568), and FFC peak hip flexor moment (PT: ρ = 0.418; peak KAM: ρ = - 0.624; peak KRM: ρ = 0.517). PT was also significantly ($p < 0.01$) associated with horizontal exit velocity (ρ = - 0.451), and, notably, multi-planar knee joint loading (peak KAM: ρ = - 0.590; peak KRM: ρ = 0.525; peak KFM: ρ - 0.509). Cohen's D effect sizes (d) revealed that faster performers demonstrated significantly greater ($P < 0.05$; d = 1.1 – 1.7) multi-planar knee joint loading, as well as significantly greater ($P < 0.05$; d = 0.9 – 1.2) FFC peak hip flexor moments FFC, PFC average horizontal GRFs, and peak knee adduction angles. To conclude, mechanics associated with faster cutting performance appear to be 'at odds' with lower multi-planar knee joint loads. This highlights the potential performance-injury conflict present during cutting.
Response to Reviewers:	Editor Comments:

In addition to the statistical queries posed by the reviewers, please also use confidence intervals and when reporting p values singular (e.g. for a single variable) please provide the actual p value not the threshold of significance. The general term or abbreviation "ES" should be exchanged for a more specific effect size abbreviation, in this instance d for Cohen's d so as to make clear to readers the effect size the value represents.

Thank you for your recommendations. We have provided actual p values for singular variables where reported. The threshold of 'p < 0.001' is provided for several variables as we wanted to keep to 3 d.p. where the values were beyond this. We have now used the 'd' abbreviation for Cohen's d effect sizes instead.

Further, please review all author submission information regarding formatting and information required, for example (as stated above with p values) and please provide ICCs (and CVs) for dependent variables.

Thank you for this. We have now included ranges which have demonstrated the reliability of the dependent variables used in our lab from pilot work.

Reviewer #1: The authors have presented an important analysis of side-step cutting linking certain characteristics to both performance and biomechanical loading at the knee. This is certainly a worthwhile and interesting area that, as the authors have pointed out, needs more attention in the biomechanics/side-step cutting literature. I have noted some areas in the specific comments below as to where I think some areas of the manuscript/analysis could be improved or value could be added to the paper. In particular; the choice to focus on frontal plane knee moments in isolation is somewhat problematic, given the multi-planar manner in which the ACL is loaded in sporting movements like side-step cutting.

I think the authors could present a bit more of a detailed approach as to what these results might mean for conditioning athletes to perform these manoeuvres. Specifically, I think the authors have more so focused on one side of where the discussion needs to go in this area - i.e. that high-performing athletes need to be conditioned to handle the higher knee loads that come with better performance - where I believe more detail could be discussed around whether there is any plausible way in which an athlete could be conditioned to perform just as well but with better mechanics from an injury perspective.

See below for some more specific comments. These are (hopefully) designed to get the authors to consider where some extra value could be added to this analysis.

Note: Page and line numbers provided are those placed by the authors, not those automatically added to the manuscript proofs.

ABSTRACT

Page 2, Line 2: Be wary of using the specific term "injury risk" in this sort of study design. Given you haven't followed-up with these athletes to see who has sustained an injury, you can't necessarily dictate if they are "at risk" of injury. Using knee loading as a proxy is a fair enough approach, but the fact that this doesn't necessarily tell us if someone is at-risk of future injury is something we have to be wary of in this sort of study.

Thank you for your comment. We appreciate that the increased joint loads increase ACL strain, which can result in rupture, yet the results from our findings do not necessarily imply that individuals are 'at risk' of injury. Therefore, we have primarily focused on the increased knee loads increasing 'ACL strain' throughout the manuscript and removed any implications for 'injury risk'. We have decided to keep injury risk in some instances where we are describing the term in a topical sense (e.g. "Research in relation to cutting technique 'injury risk' factors has received greater attention"), as this supports the narrative of the manuscript.

Page 2, Line 4: the full format of the abbreviation COD has not been introduced prior to first use in the abstract.

Thank you for your comment. This has been modified.

Page 2, Line 5: "Knee adduction moments" - this is probably a preference thing but I prefer to use the term abduction moments when discussing in an ACL injury context (if you are using external moments that is), given this is what loads the ligament. I will likely comment on this later in the manuscript but why is there no consideration given to other moments, given the likely multiplanar mechanism of ACL injuries (see Quatman CE et al. A 'plane' explanation of anterior cruciate ligament injury mechanisms: A systematic review. Sports Med. 2010, 40; Kiapour AM et al. Timing sequence of multi-planar knee kinematics revealed by physiologic cadaveric simulation of landing: Implications for ACL injury mechanism. Clin Biomech. 2014, 29; Shin CS et al. Valgus plus internal rotation moments increase anterior cruciate ligament strain more than either alone. Med Sci Sports Exerc. 2011, 43; Kiapour AM et al. Strain response of the anterior cruciate ligament to uniplanar and multiplanar loads during simulated landings: Implications for injury mechanism. Am J Sports Med. 2016, 44; + more…)
Thank you for your suggestion. “Knee adduction moments” has been modified to “external knee abduction moments” throughout the manuscript. We have also considered a more multi-planar approach to our analysis. We discuss this in comments below.

Page 2, Line 15: "Faster performers" - it looks as if a form of sub-group comparison has taken place here. Presumably this will be further explained in the full-text, but there is no real description of this in the abstract (i.e. how this process was undertaken).

Apologies, our mistake. We have included Cohen’s D effect sizes in the description of our statistical approach to determining “faster performers”.

Page 2, Line 19-20: I agree with this concept, that athlete's need to be able to withstand higher loads that likely come with faster performance - but the flipside of this is whether athletes can be trained to perform these just as fast without the high knee loads. This is something that can't be deduced by your study but probably needs to be considered (might be discussed in the full-text though).
Thank you for your comment. We have attempted to highlight this issue in an altered concluding sentence at the end of the abstract.

INTRODUCTION

Page 3, Line 32-33: "Knee adduction…moments" - as noted in the abstract, it might need to be clearer that this is seemingly referring to internal joint moments, as external knee ABDuction moments seem to be referred to more in an ACL injury risk context.
In light of your comment in the abstract, “knee adduction moments” has been modified to “external knee abduction moments” throughout the manuscript.

Page 3, Line 34: "potentially lead to increased strain on the ACL" - I think you can be a bit stronger in this statement, there is a lot of evidence out there that highlights elevated strain on the ACL with these joint moments (in addition to what you have also see Kiapour AM et al. Strain response of the anterior cruciate ligament to uniplanar and multiplanar loads during simulated landings: Implications for injury mechanism. Am J Sports Med. 2016, 44; Kiapour AM et al. Timing sequence of multi-planar knee kinematics revealed by physiologic cadaveric simulation of landing: Implications for ACL injury mechanism. Clin Biomech. 2014, 29; Withrow TJ et al. The effect of an impulsive knee valgus moment on in vitro relative ACL strain during a simulated jump landing. Clin Biomech. 2006, 21; Taylor KA et al. Measurement of in vivo anterior cruciate ligament strain during dynamic jump landing. J Biomech. 2011, 44; Oh YK et al. What strains the anterior cruciate ligament during a pivot landing? Am J Sports Med. 2012, 40).
Thank you for your comment. We have tried to be more explicit in our terminology, as well as adding some references you’ve suggested to further consolidate the statements in this section.

Page 3, Line 36: You could potentially add a couple of extra studies that have made some inferences about performance and mechanics during cutting to this citation - Dai B et al. The effects of 2 landing techniques on knee kinematics, kinetics, and performance during stop-jump and side-cutting tasks. Am J Sports Med. 2015, 43;

Mornieux G et al. Anticipatory postural adjustments during cutting manoeuvres in football and their consequences for knee injury risk. J Sports Sci. 2014, 32.
We appreciate your suggestions. We have added an extra study (Dai et al.) to this section – we would like to add more, but are trying to be wary of the reference limit stipulated by the journal which we had already slightly exceeded.

Page 3, Line 39-48: You have mentioned numerous studies have elucidated mechanical determinants of performance for COD, yet only outline the findings of one (Marshall et al.) in this section. A more expanded discussion of the literature here would be preferable.
Thank you for your feedback. This section has been amended with a more detailed outline of each of the studies' findings.

Page 4, Line 58-67: The work of Staynor et al. from the University of Western Australia is fairly relevant to this section - as his thesis (recently completed) focused on preparatory mechanics and their link to knee loading during side-step cutting. I'm not sure whether this work is completely published yet but there will be abstracts of this work available that he presented at recent conferences, namely the ISBS Conference in Auckland and the Sports Medicine Australia Conference in Perth this year (2018). This would provide the "injury risk" perspective for investigating this penultimate foot contact.
Thank you for this comment. It was beyond the scope of this investigation to examine preparatory trunk mechanics as we wanted to develop on the previous work from our lab. We have now addressed this in our limitations and recommended that future research looks to expand on this to elucidate how much 'pre-rotation' occurs in the steps prior to FFC.

METHODS

Page 5, Line 91: It seems odd to reiterate the aims in the methods here - shouldn't these statements be placed as specific aims at the end of the introduction?
Thank you for your suggestion. We have removed these from the methods and added specific aims to our introduction instead.

Page 6, Line 115-116: "Performance time" - this is somewhat of an issue with side-step cutting performance research, that "performance" is measured by the time it takes the athlete to complete the run-up, cut and exit. While this does provide a holistic measure of performance and should be used, other more detailed measures may be required to understand how well someone performs the actual "cutting" aspect. For example, someone who is a really quick straight line runner could perform the actual cut somewhat poorly yet their straight line speed brings up their performance. Something like the change of direction deficit (Nimphius S et al. Change of direction deficit: a more isolated measure of change of direction performance than total 505 time. J Strength Cond Res. 2016) could be beneficial, although if you don't have their straight line speed I don't think this is possible. Your 3D motion capture data (e.g. tracking marker velocities) could allow you to capture some more specific aspects of the cutting performance (e.g. entry and exit times, foot plant times etc.) (see Bradshaw RJ et al. Comparison of offensive agility techniques in Australian Rules football. J Sci Med Sport. 2011, 14 as an example of this). Doing this might give you a better understanding of what specific aspects of cutting performance are associated with your injury risk metrics (e.g. someone who has a fast entry time might have higher KAMs). There might potentially be some discussion on this later in the manuscript but I wanted to make note of this in the methods section. (Looking further on I can see there are some relationships made to exit velocity…)
Thank you for your comment. We acknowledge the issue with performance time and as such have also utilised approach and exit velocity in our analysis. We were unable to measure a time to a certain point because capture volume restrictions limit the ability to measure exit times.

Page 7, Line 122-124: It appears that this is an anticipated cutting task, which differs to unanticipated tasks used in a lot of ACL injury risk literature. Is there a reason this was done? Again, there might be some discussion on this later but wanted to mention it in the methods.

Thank you for this comment. We wanted to examine the biomechanical determinants of faster COD speed performance, which, by its definition, is pre-planned. If we used an unanticipated task, this is actually agility performance and is therefore influenced by the perceptual and cognitive capabilities of an athlete. This was not the focus of the study. In fact, the performance studies have all used pre-planned tasks, and injury-related study's studies have used pre-planned tasks, too (Jones, Kristianslund). We were continuing on from the work of Havens which used a pre-panned task (the only study to our knowledge to consider both aspects). And finally, previous investigations which have used unanticipated side-stepping tasks have mainly used flashing lights/arrows, which lack ecological validity to the actions performed in sport. The type of stimuli and timing of stimuli affect COD biomechanics which makes it difficult to control for and administer. Pre-planned movements do occur in sport.

Page 7, Figure 1: Looking at this figure it appears to illustrate a 90 degree cut, yet yours was a 60 degree cut. Wouldn't it be more preferable to illustrate the specific set-up for the task you used?
Thank you for identifying this. We have re-configured our diagram in light of this issue.

Page 8, Line 156-157: "Pre-determined cut-off frequencies with 12 and 25 Hz force" - what method was used to determine these cut-off frequencies (e.g. existing literature, residual analysis, visual inspection of data)? This needs to be clarified to ensure this wasn't just an arbitrary selection. It may also be important to consider some of the literature around matched vs. unmatched cut-off frequencies (see Kristianslund E et al. Effect of low pass filtering on joint moments from inverse dynamics: Implications for injury prevention. J Biomech. 2012, 45; Kristianslund E et al. Artefacts in measuring joint moments may lead to incorrect clinical conclusions: The nexus between science (biomechanics) and sports injury prevention! Br J Sports Med. 2013, 47; Roewer BD et al. The 'impact' of force filtering cut-off frequency on the peak knee abduction moment during landing: Artefact or 'artifiction'? Br J Sports Med. 2014, 48) and how this might impact your joint moment values.
Thank you for highlighting this. We have now provided more information regarding our methodological approach. Roewer et al. argue that matched frequencies affect the signal and results in blunted response, potentially over smoothing the data. Also, we wanted to inspect the GRF determinants and were gain cautious about over-smoothing the data. Even since the recommendations by Kristianslund, numerous studies continue to use mismatched COFS. Havens et al. (2015) used large mismatched cut-off frequencies – this is the study that most closely aligns with ours and so we decided mismatched would be the most appropriate approach.

Page 8, Line 161-169: There is some discussion here about breaking the cut into phases, but I'm not sure it's been made clear where the peak KAM has been extracted from. The peak value during weight acceptance would be most consistent with existing literature - but it would just be nice for it to be a bit clearer where the data has been taken from.
Thank you for your comment. A reference to 'Table 1' has now been made in the methods section, where the definition is provided which states it has been extracted from the weight acceptance and propulsion phase during the final foot contact.

Page 9, Line 183: As noted earlier, the selection of just peak KAM as the "injury risk" variable is OK, but probably doesn't acknowledge the multi-planar nature of ACL injuries - particularly the combination of frontal and transverse plane loading. Was there any consideration of using one-dimensional statistical parametric mapping (SPM1D) to provide a greater understanding of the relationship between cutting "performance" and multi-planar knee loading (see Pataky TC et al. Vector field statistical analysis of kinematic and force trajectories. J Biomech. 2013, 46; Pataky TC et al. Zero- vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. J Biomech. 2015, 48; + some more papers from this research group on SPM1D).

Thank you for this suggestion. We argue that looking at the whole curve will not really tell you anything, as, based on observational studies, ACLs go early in ground contact when the load the knee is exposed to exceeds to tolerance of the ACL. We have now attempted to explore predictors of knee flexor, rotation and abduction moments to acknowledge the 'multi-planar' nature of ACL injuries.

Page 9, Line 191-192: This is a little confusing as to what the final alpha level was set at. It sounds like you have corrected for multiple tests, yet it still states here that the alpha was set at < 0.05 following correction.
Thank you for your comment. We have addressed this by stating the correction was multiplied by the number of correlations explored.

RESULTS

Page 10, Line 194-208 (more of a methods comment though): I'm not sure some of these variables have been fully explained, or that all of the correlations tested were acknowledged in the methods. I don't recall seeing a definition for what defined "horizontal approach/exit velocity" (i.e. what portion of the cut were these over?), or recall it being stated that correlation statistics were planned to be ran on overall performance time and some of these other performance measures.
Thank you for your comment. Readers are referred to 'Table 1' for more in-depth descriptions of the biomechanical variables of interest. We acknowledge the importance of presenting some clarification of these within the methods; however, due to the large number of factors we were looking to investigate, we decided that presenting these in table format would allow the reader to refer to them in a more uniform, easy to read way.

Table 2: I think it needs to be clear what the positive values for the KAM variable represent (and perhaps some of the other variables to). If this value is extracted from weight acceptance I'd expect the positive KAM value to be an external abduction moment, however I don't believe this has been made clear.
Thank you for highlighting this issue. In light of the above comments, we have changed the convention to 'external knee abduction moment' throughout and defined more clearly in Table 1.

DISCUSSION

Page 11, Line 230: In line with some earlier comments, stating the term "mechanical knee joint loading" is at odds with what you've done in just focusing on frontal plane loads. I think if your analysis remained as is you would have to state "frontal plane knee loading" here.
Thank you for this recommendation. We have decided to add another layer to our analysis for which we have grouped peak knee abduction, rotation and flexion moments together as a means of evaluating overall mechanical knee joint loading. Hopefully this sheds more light on the 'multi-planar' nature of knee loading during cutting and allows for more detailed discussion.

Page 12, Line 240: Again, using the specific term "injury risk" here is probably unwise, given you don't know whether these people who exhibited such characteristics actually are at higher risk of injury (we can't determine this without prospective follow-up). Something like "…related to both performance and biomechanical factors linked to ACL loading" might be more appropriate.
Thank you for your comment. As mentioned above, we have now primarily focused on the analysis of increased knee loads with respect to increased ACL strain, and not increased 'injury risk', throughout the manuscript.

Page 12, Line 239-250: I'd argue that higher peak knee extensor moments themselves could be suggested as hazardous to the ACL, particularly early on after initial contact. This is where a more multi-planar approach to your "injury risk" component could be valuable.
Thank you for your comment. As mentioned above, we have now considered a multi-planar approach to our analysis of knee joint loading. This means our data has been re-analysed and hopefully bolsters the points on mechanical knee joint loading in our discussion.

Page 12, Line 251-252: "frontal plane hip mechanics were predictors of a 90 degree cutting task" - presumably you mean predictor of performance? Missing words from this sentence?
Thank you for highlighting this. We have added that they were predictors of performance.

Page 12, Line 251-261: The body positioning (of the hip) with respect to the centre of pressure is also something to consider with the moments generated about the hip (i.e. someone who's hips are placed further back from the centre of pressure would likely generate greater external flexor moments at the joint). I don't have any specific answers here but it could be that different performers or those who generate higher knee loads exhibited different postures in this respect.
Thank you for your comment. We agree, but we did not examine step length – COM to COP distance in the sagittal plane – so it would all be speculative. McLean has found that increased hip flexion posture increases knee abduction moments, it certainly would give rise to a higher hip flexor moment along with greater trunk flexion. Thus, you have three possible factors, greater hip moments, related to initial hip and trunk postures and greater GRF from faster approaches.

Page 13, Line 285-288: I think there's more discussion to be had around this (and this might be moer suited to later in the discussion or in the practical applications section) - specifically as to how this lateral leg plant distance characteristic should be approached. You mention that we should be wary of changing it as it has quite a beneficial effect on performance, but it also likely has the largest impact on the frontal plane knee moment. It begs the question - should these athletes be taught to place their leg quite laterally and be trained to be able to withstand high knee loads; or should they be taught to bring their leg in but be able to generate greater forces through this propulsive movement to still accelerate themselves just as fast; or both? Difficult question to answer but some discussion could be worthwhile.
Thank you for this comment. We have expanded on this in our practical recommendations, which we hope provides the reader with more information with regards to coaching LLP within each individual's context.

Page 14, Line 289-305: I'm not sure this point needs as much discussion/explanation as is done here. This seems pretty simple - greater forces directed towards (or more so away) where you want to go will make you faster.
Thank you for this. We have reduced the discussion regarding this point.

Page 15, Line 330-331: "These findings substantiate previous research which has suggested that shorter GCT FFC are a determinant of COD performance." This could just be a picky thing with terminology, but I'm not sure that shorter ground contact times need to be substantiated as a performance determinant of cutting by linking them to things like exit velocity. I suppose, to me, a shorter ground contact time is another characteristic that could be used as a performance metric for cutting (i.e. if you spend less time on the ground during the step then you are doing it better).
Thank you for this comment. Nearly all studies investigating the determinants of COD from a performance perspective have investigated GCT as a factor and it was the scope of this study to build on this.

Page 15-16, Line 336-340: As noted earlier, I think this viewpoint ignores the other side of the argument, that we could potentially train technique to be better from an injury risk perspective, while conditioning an athlete to be able to perform the movement "better" with this sort of technique.
Thank you for this comment. We have attempted to expand on this issue in the practical applications with our thoughts on how best to accommodate for this inherent conflict.

PRACTICAL APPLICATIONS

Page 16, Line 344-346: As above, is this the only way? Do cutting programs emphasising performance improvements need to stay the same and we just have to deal with the added risk to the lower limb? Or do we reconsider how to teach fast side-step cutting by starting to acknowledge the injury component within this? You start to

discuss this a little bit as you get into this section, but I think this is the important point that stems from this work so it could have more of a focus.
Thank you for highlighting this issue. As above, in our practical applications, we have attempted to provide a more detailed solution to this important point from our findings.
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Reviewer #2:

Thank you for the opportunity to review "Biomechanical Determinants of Performance and Knee Joint Loads During a 60 degree Cutting Maneuver in Soccer Players." I read this manuscript with interest. In this study, the authors analyze the mechanics of soccer players performing a 60-degree cutting task. They use correlation to identify relationships between mechanics and performance and injury risk variables. The also use paired testing to determine differences between fast and slow performers. Overall, this is well written. I do have some concerns about the methodology and interpretation of the findings.

My biggest overall concern about this manuscript is with the statistical approach, for 3 reasons. First, you seem to have a lot of variables of interest, and I'm not sure that your study is powered for that (with only 34 subjects, not hundreds). Second, you use correlations but your aims don't necessarily match (determinants of, not relationships between). Finally, when comparing the data between fast and slow performers, you do not statistically control for the difference in speed in variables like force and moment that are affected by this. It is not a surprise that forces and moments will be greater in faster performers- force is related to acceleration. This limits your interpretation.

One of my overall comments is about the use of 3 variables to represent performance- performance time, approach velocity and exit velocity. Considering that these three variables are highly related to each other (Table 2), and that they significantly differ between fast and slow performers (Table 4), I don't understand the utility of all three. They all seem to represent the same thing. Consider only using performance time- this would streamline your interpretation and make your recommendations clearer.

Finally, this study asks a similar question (injury/performance) to one previously published- Havens and Sigward 2015- with a similar task- 60 degree cut (they reported two tasks- 45 and 90 cuts). More emphasis should be made on the similarities between the results of the studies, especially between the 45 and 60 degree cuts since these are very similar angles. It should also be clearer what makes this study different and therefore worth publishing (besides the slightly larger cut angle).

Specific comments follow.

Abstract
Line 7- How were these pre-determined?
Thank you for highlighting this. We have removed ‘pre-determined’ and instead stated relationship between COD kinetic and kinematics with performance and peak KAMs.

Introduction
Line 45: What is GCT?
Apologies, our error. We have now defined this term (i.e., ground contact time).

Lines 58-67: I'm not sure what this paragraph adds to the overall story. You use the term stride adjustments here, but I'm not sure how this relates to your variables of interest.
Thank you for your comment. We are highlighting the importance of the PFC here – involved in braking and preparation for the FFC. In the opening sentence, for clarity, we have removed the term ‘stride adjustment’ and included that COD is a ‘multi-step action’ and preliminary deceleration is needed for cutting. Neither Marshall et al. (2015) and Havens et al.’s (2015) work have examined this, either, so there is scope for further investigation with which our work has hopefully explored.

Line 71: These authors determined COM-COP distance, when rotated relative to the body's progression, was predictive. Lateral leg plant distance has been defined differently in different papers- Perhaps referencing Table 1 where you define it.

	Thank you for highlighting this. We have attempted to address this in the introduction by acknowledging the differences in definitions and have made reference to 'Table 1' where appropriate. Line 76: Havens and Sigward do present findings for the 90-degree task. There was not an overlap between predictors for injury and performance, but predictors for both injury and performance are presented. The authors conclude that training technique for performance based on this data is not as clear as 45 degree cut. Please revise. Also, considering that your task is 60 degrees, very close to 45, I'm not sure that bringing up a 90 degree task adds to your argument. Thank you for your comment. We have added Havens and Sigward's findings for the 90 cut to our introduction. We have also re-evaluated the description of our cutting maneuver and amended Figure 1 in light of this change. We describe that what we essentially did was provide a 'window' (i.e., between 70 and 90 degrees) for which to run through. We hope this provides more clarity on the issue and should allow for more comparisons to be made with regard to the abovementioned study. Methods Lines 92-93: There seems to be a mismatch between your statistical approach and your aims. With correlation, you can ask questions like, "will these be related?". But you cannot determine factors (aim a). You also seem to have 3 aims, with the third one about differences between fast and slow performers. Consider adding this to the sentence with your aims. Thank you for highlighting this issue. We have attempted to address this by removing the stipulation that our investigated factors 'determine' performance/injury-risk and instead use terms such as 'related' and 'associated' throughout the manuscript. Line 119: Why 90 and 70 Degrees? Thank you for your comment. We have explained that this provided a cutting 'window' for the participants to accelerate though. More detail on this matter has been provided in the responses above. Line 128: Please report subjects' foot dominance. Do you think that it would matter if subjects are performing a sidestep cut with their non-dominant foot? Thank you for this comment. Due to the configuration of the lab, we were only able to examine cutting maneuvers off the right leg. However, research shows that there may not be much difference in cutting mechanics between limbs (Greska et al. 2017). We have now acknowledged this as a limitation in our discussion. Line 183: I think that approach velocity should be included in this list based on your results. Thank you for your comment. We decided to exclude approach velocity in this list as it isn't directly a component of the COD action, but merely a potential associate. Discussion Line 235: Consider changing 'indicative of' to 'correlated with'. Thank you for your suggestion. We have changed all associative terms where appropriate. Line 251: Again here, I'm not sure of the utility of comparing your 60 degree task with a 90 degree task. Your 60 degree task gave similar results to the 45 degree task reported by Havens and Sigward. This is not a surprise, since these are very similar cut angles. Thank you for your comment. As discussed in an earlier comment, we have re-evaluated our cutting task description (i.e., 70-90 degrees instead of 60). This allows for more comparable discussion between our study and Havens et al. (2015). Lines 265-273: I'm glad that you bring up that faster velocities and accelerations are related to higher loading here. But, I'm not sure that I agree with the argument that they 'add emphasis to the performance-injury risk conflict'. I don't see how this adds to the argument beyond your results of performance time. Thank you for your comment. It is problematic because faster athletes experience

	greater loads, thus potentially ACL strain. We can't instruct athletes to run slower because this will negatively affect performance. Hence, the conflict. We have re-worded this slightly in light of your comments. Line 277: This reference doesn't seem to match the argument. I would expect that this article (reference 39) would demonstrate that approach and exit velocity are better at indicating COD performance than performance time, but that is not the purpose or result of this study. I still think that you need a stronger argument for including these variables. Apologies, this appears to be a misplaced reference. We have added the intended one and re-worded our rationale. Line 301: 60 degree not 90 degree cut? There are multiple times that I caught that a 90 degree and not 60 degree cut task is referenced. Please carefully revise accordingly. Thank you for highlighting this issue. This has been revised. Line 332: What do you mean by technical variables? Thank you for your comment. This has been changed to 'technique'. Figure 1 This shows a 90 degree cutting task, not 60. Thank you for highlighting this. We have re-configured Figure 1. Table 1 What is 'horizontal' approach and exit velocity? Does that mean 2D, resultant of ML and AP? Exit velocity says 'resultant' but approach does not. Thank you for this comment. We have re-evaluated our definitions of both horizontal approach and exit velocities, from which detailed explanations of each are provided for within Table 1. For all abbreviations in table, please write out the words to begin the definition. HBFR: what is this? Consider removing all abbreviations in definitions unless already defined in table. Thank you for this comment. We have written out the words to begin definitions and have added an abbreviations column within the table. Lateral leg plant distance- was this value rotated relative to the progression of the individual? COM-COP distance projected ono the global ML plane does not necessarily represent the ML distance relative to the body, considering that the body is likely rotated out of alignment with the global system. Consider using a rotation matrix to fix this. Thank you for this comment. We considered a number of ways of examining lateral leg plant (lateral distance between centre of mass of the foot to proximal end of the pelvis). However, the option chosen we felt provided a technique parameter that would directly result in the generation of medial force production. The COM-COP pressure distance would also factor in generation of anterior-posterior braking force and therefore, may not directly associate with cutting performance. The later variable may also be impacted by other technical parameters such as lateral trunk flexion. The lateral leg plant distance is analogous with cut width reported by Kristianslunds et al (2014) and lateral leg plant distance (Jones et al., 2015). Lateral trunk flexion angle- what is used to determine that this vertical line is aligned with the trunk? This seems to be a representation of pelvis angle and not trunk, which could be independently side-bent relative to the pelvis. Thanks for this opportunity to clarify. The trunk angle is determined relative to the lab co-ordinate system (vertical line). Peak hip, knee ankle joint flexion angles: Definition seems incomplete Thanks for highlighting this. We have addressed these definitions and made reference to 'Table 1' where appropriate.

	True cut angle- says 90 deg COD task Thank you for highlighting this. It has been changed to 70-90 degree COD task.

Title Page (Showing Author Information)

Biomechanical Associates of Performance and Knee Joint Loads During an 70-90° Cutting Maneuver in Sub-Elite Soccer Players

Original Research

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Alistair J. McBurnie [#], Thomas Dos'Santos, Paul A. Jones

Human Performance Laboratory, Directorate of Sport, Exercise, and Physiotherapy, University of Salford, Greater Manchester, United Kingdom

[#] Corresponding Author: Alistair James McBurnie

Telephone: 07986843516

Email: Alistair.McBurnie@manutd.co.uk

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Alistair James McBurnie

Directorate of Sport, Exercise and Physiotherapy. University of Salford, Salford, Greater Manchester, UK

Alistair.McBurnie@manutd.co.uk

+44 7986843516

Biomechanical Associates of Performance and Knee Joint Loads During an 70-90° Cutting Maneuver in Sub-Elite Soccer Players

ABSTRACT

The aim of this study was to explore the ‘performance-injury risk’ conflict during cutting, by examining whole-body joint kinematics and kinetics that are responsible for faster change of direction (COD) performance of a cutting task in soccer players, and to determine whether these factors relate to peak external multi-planar knee moments.34 male soccer players (age: 20 ± 3.2 yrs; mass: 73.5 ± 9.2 kg; height: 1.77 ± 0.06 m) were recruited to investigate the relationships between COD kinetics and kinematics with performance and multi-planar knee joint moments during cutting. Three-dimensional motion data using 10 Qualisys Oqus 7 infrared cameras (240 Hz) and ground reaction force (GRF) data from two AMTI force platforms (1200 Hz) were collected to analyze the penultimate (PFC) and final (FFC) foot contacts. Pearson’s or Spearman’s correlations coefficients revealed performance time (PT), peak external knee abduction moment (KAM) and peak external knee rotation moment (KRM) were all significantly related ($P < 0.05$) to horizontal approach velocity (PT: ρ = - 0.579; peak KAM: ρ = 0.414; peak KRM: R = - 0.568), and FFC peak hip flexor moment (PT: ρ = 0.418; peak KAM: ρ = - 0.624; peak KRM: ρ = 0.517). PT was also significantly ($p < 0.01$) associated with horizontal exit velocity (ρ = - 0.451), and, notably, multi-planar knee joint loading (peak KAM: ρ = - 0.590; peak KRM: ρ = 0.525; peak KFM: ρ - 0.509). Cohen’s D effect sizes (*d*) revealed that faster performers demonstrated significantly greater ($P < 0.05$; d = 1.1 – 1.7) multi-planar knee joint loading, as well as significantly greater ($P < 0.05$; d = 0.9 – 1.2) FFC peak hip flexor moments FFC, PFC average horizontal GRFs, and peak knee adduction angles. To conclude, mechanics associated with faster cutting performance appear to be ‘at odds’ with lower multi-planar knee joint loads. This highlights the potential performance-injury conflict present during cutting.

Key words: change of direction; anterior-cruciate ligament knee injury; whole-body kinematics; ground reaction forces; external knee abduction moments.

INTRODUCTION

Change of direction (COD) maneuvers are frequent actions that occur in soccer (2). Notational analysis in FA Premier League soccer players has found that an average of 609 turns occurring within 0-90° can be made during a single game (2). Thus, the ability to quickly change direction in response to constantly changing circumstances (i.e. opposition, ball) can be considered a pivotal component to successful performance in multi-directional sports, such as soccer (44). That said, COD maneuvers, such as cutting, have been identified as key actions that are associated with non-contact anterior cruciate ligament (ACL) injuries (3,13,47) with amplified multi-planar knee joint loading (i.e., flexion, rotational, and abduction loading) whilst the foot is planted often reported (5,6,17,26,45). Such loads are associated with increased strain on the ACL (37,38,45). Less is understood regarding the mechanics concerning optimal performance in such actions, with only a handful of studies having examined the mechanics of faster COD tasks (4,10,17,31,36). Resultant research findings have demonstrated that medial trunk rotation (31), as well as braking and propulsive forces in shorter ground contact times result in faster COD performance (10,41). This holds great importance for coaches to develop training programs that improve COD performance whilst reducing the risk of ACL injury.

The mechanical determinants of performance have been previously elucidated (10,18,41–43); however, there are a limited number of studies to date that have examined the combination of kinetic, kinematic, and technical factors which determine COD speed performance (31). Marshall *et al.* (31) explored a whole-body analysis of a 75° cutting task, in which they uncovered five key biomechanical performance associates: peak ankle extensor moment and power, pelvic frontal plane control, trunk rotation towards the intended direction of movement, and ground contact time (GCT). The authors suggested the development of force production about the ankle, improved proprioceptive control of the pelvis during single-limb support, and rotation of the torso towards the intended direction were all technique factors contributing to superior COD performance.

Research in relation to cutting technique injury risk factors has received greater attention (5,6,18,24,26,29,40), with frontal plane knee mechanics being recognized as key characteristics associated with ACL injuries. A number of studies have suggested that initial knee adduction angle (KAA) (26,29), lateral leg plant distance (5,6,17,26) and initial lateral trunk flexion (5,6,24,26) are technique factors which, coupled with high plant foot GRF vectors, likely dictates the magnitude of external knee abduction moments (KAMs). Consequently, addressing these aforementioned determinants of KAMs could be a viable method to reduce knee joint loading and subsequent ACL strain during cutting (5,6,18,24,26,29,40).

COD is a multi-step action with which preliminary deceleration is required prior to turn initiation (10,11,25,26). It seems that if a greater proportion of forward momentum can be overcome by applying large GRFs during the penultimate foot contact (PFC), then the GRFs experienced in the final foot contact (FFC) prior to direction change may be mitigated and subsequently reduce the KAMs experienced (11,25,26). Equally, recent findings have reported that this deceleration strategy may also be beneficial for COD performance, due to the subsequent decreased time spent braking in the FFC (10). Although insightful, this study was limited to solely investigating COD kinetics in an isolated 180° pivot. As such, a more comprehensive biomechanical assessment of the role of the PFC in relation to cutting performance is warranted.

Havens and Sigward (17) explored the potential 'performance-injury risk' conflict, investigating the joint characteristics related to completion times of 45° and 90° cuts, with the aim of revealing which factors were associated with performance and frontal plane knee joint loading (i.e., peak KAMs). From this, "medial-lateral center of mass-center of pressure distance" (analogous to lateral leg plant distance; Table 1) was found to be the only variable that was predictive of both performance times and peak KAM (45°). Although definitions of lateral leg plant (LLP) distance may differ slightly within the reported literature (e.g., whether this distance is relative to pelvic position or to the frontal plane), the findings of Haven's (17) work highlight the role LLP distance as a performance factor (23) and in increased knee joint loading (5,6,17,26) of COD actions. Clearly, this conflict needs to be investigated further in order to improve ACL injury mitigation and COD speed training recommendations. Furthermore, Havens and Sigward (17) presented different findings in relation to their 90° cutting task, (i.e., internal knee extensor moment and hip rotation angle were associated with performance time and peak KAM), so it could be stipulated that the recommended technique for 45° cutting (i.e., emphasizing sagittal plane motion as a product of decreased torso and lower-body positioning in the frontal plane) may not be applicable to a 90° cut, and may reduce performance times without alleviating heightened mechanical knee joint loading.

The aim of this study was to investigate the whole-body joint kinematics and kinetics that are responsible for faster cutting performance in professional, semi-professional, and collegiate soccer players, and whether these factors are related to multi-planar knee joint loads (i.e., peak KAM, KRM, and KFM), and thus potential ACL injury risk. This was approached using three primary objectives: (a) to determine which biomechanical factors were associated with faster COD performance of an 70-90° cutting maneuver; (b) to identify which of these variables were associated with peak KAM, KRM, and KFM; and (c) to compare the biomechanical differences between faster and slower performers during the 70-90° cutting task. It was hypothesized that LLP distance, medial-lateral GRFs and PFC kinetics would be associated with faster completion times, whilst LLP distance and PFC kinetics would be related to both performance and multi-planar knee joint loading.

METHODS

Experimental Approach to the Problem

A cross-sectional study design was used to evaluate whole-body kinematics and kinetics during a 70-90° cutting maneuver using 3D-motion and GRF analysis over a single testing session. Pearson's or Spearman's correlation coefficients were used to evaluate the association between pre-determined biomechanical factors of performance (Table 1). Biomechanical differences between faster and slower performers during the maneuver were assessed using independent T-tests and Cohen's d effect sizes, as used previously (20). A minimum sample size of 33 participants was determined from an *a-priori* power analysis using G-Power (Version 3.1, University of Dusseldorf, Germany) based upon a previously reported correlation value of 0.45 (LLP to KAM), a power of 0.8 and type 1 error or alpha level 0.05 (12).

Subjects

Thirty-four male soccer players (age: 20 ± 3.2 yrs; mass: 73.5 ± 9.2 kg; height: 1.77 ± 0.06 m) participated in this study. These were considered to be experienced high-standard players (i.e., collegiate, semi-professional, or professional), who were all approaching the mid-point of their respective playing seasons. Participants were required to be free from injury and/or display no chronic physical pathologies that may have affected performance of the task. Before completion of the task, the outline of the testing procedure was communicated and written informed consent from all participants was acquired. Parental/guardian consent was ascertained for participants who were under the age of 18 and approval for the study was granted by the University's ethical committee.

Procedures

Cutting Task

Participants were first required to perform a standardized warm-up, which included 5 minutes of heart rate elevation exercise (i.e., 6 low-intensity laps of the performance track) followed by dynamic stretches and activation exercises (i.e., bodyweight squats, walking lunges, bilateral jumps), before executing 5-6 familiarization trials of the cutting task. To record performance time (PT) of the 70-90° cut, two pairs of Brower single beam timing gates (Draper, UT) were used and aligned to approximately hip height (49) and two force platforms were embedded within the track. The initial set of timing gates were positioned 5 m away from the center of the final force platform (FP), with another pair of timing gates set up 3 m between 70° and 90° to the center of the FP to mark the finishing point of the task; this presented the athlete with a cutting 'window' with which to accelerate through (Figure 1). Participants were then instructed to perform six 'good' trials of the cutting task, where they would aim to sprint at maximal effort through the first set of timing gates, arriving and planting their left foot on the first FP (i.e., PFC), and then their right foot on the final FP (i.e., FFC), before instantaneously cutting 70-90° to the left and running through the final set of timing gates (Figure 1). For a trial to be considered 'good', the following criteria was set: (1) a straight approach into the turn without curvature/premature turning prior to FFC; (2) FFC landing in the central portion of the final FP, ensuring a homogenous distance of travel between trials.

****Figure 1 near here****

Biomechanical Analyses

To approximate motion of body segments during the cutting task, reflective markers (14 mm spheres) were fixed bilaterally, using double-sided adhesive tape, on the following bony landmarks: 5th, 2nd and 1st metatarsal heads, medial and lateral malleoli, medial and lateral epicondyles, greater trochanter, anterior superior iliac spine, posterior superior iliac spine, iliac crest, acromion process, mid-clavicle and 7th cervical vertebrae. A 'cluster set' (i.e., 4 retro-reflective markers attached to a lightweight rigid plastic shell) was also fastened to the participant's thighs and shins (both left and right) in order to approximate segmental motion during dynamic trials. Ten Qualisys Oqus 7 (Gothenburg, Sweden) infrared cameras (240 Hz) were used to record the three-dimensional motions of the markers whilst performing the cutting task, interfaced through Q-Track Manager software (version 1.10.282, Gothenburg, Sweden). Two AMTI (600 mm X 900 mm) (Advanced Mechanical Technology, Inc, Watertown, MA) FP's (Model number: 600900) embedded into the running track were used to record GRFs from both the final and penultimate foot contacts. FP sample frequency was set at 1200 Hz.

From a static trial, a 6-degree-of-freedom kinematic model of the lower extremity and trunk was created for each participant, including trunk, pelvis, thigh, shank and foot, using Visual 3D software (C-motion, version 3.90.21). This kinematic model was used to quantify the motion at the hip, knee and ankle joints using a Cardan angle sequence (15). The local coordinate system is defined at the proximal joint center for each segment. The static trial position is designated as the participant's neutral (anatomical zero) alignment, and subsequent kinematic measures were related back to this position. Lower limb joint moments were calculated using an inverse dynamics approach (48) through Visual3d software (C-motion, version 3.90.21) and were defined as external moments. Based on the recommendations from Roewer *et al.* (35) and residual analysis, joint coordinate and force data were smoothed in visual 3D with a Butterworth low pass digital filter with pre-determined cut-off frequencies of 12 and 25 Hz, respectively. Segmental inertial characteristics were estimated for each participant (7). The model utilized a CODA pelvis orientation (1) to define the location of the hip joint center. The knee and ankle joint centers were defined as the mid-point of the line between lateral and medial markers. The trials were time-normalized for each participant, with respect to the GCT of the 70-90° cut. Peak and average GRF, peak joint moments, and peak joint and segment angles with respect to range of motion were classified during the plant phase (i.e., initial contact to toe-off; Table 1). Initial contact was defined as the instant after ground contact that the vertical GRF (vGRF) was higher than 20 N and end of contact was defined as the point where the vGRF subsided past 20 N for both PFC and FFC (Table 1). The weight acceptance phase of ground contact was defined as from the instant of initial contact (vGRF > 20N) to the point of maximum knee flexion during ground contact, as used previously (17,25). The push-off phase was determined as the instant after maximum knee flexion to subsequent toe-off (vGRF < 20N). Participant 'true' cut angle and participant center of mass (COM) horizontal velocity during approach and exit of the maneuver were also calculated (Table 1). Definitions of all biomechanical variables of interest are provided in 'Table 1' and have previously demonstrated good reliability (ICC's ≥ 0.70; CV% ≤15%) in pilot work from our lab, which used a subset of this sample (n = 10) (8).

****Insert Table 1 here****

Statistical Analyses

All statistical analyses from the data collected were performed using SPSS statistical analysis software (version 23.0, SPSS, Ince., IL, USA) and Microsoft Excel (version 2016, Microsoft Corp., Redmond, W.A., USA). Preliminary normality tests were taken in order to determine whether Pearson's product correlation or Spearman's rank correlation was to be used. These correlation tests were employed to determine which biomechanical variables (Table 1) of interest were associated with PT, exit velocity, peak KAM, peak KRM, and peak KFM during the 70-90° cut. Resultantly, correlation strength was based on the following parameters: small (0.10 - 0.29), moderate (0.30 - 0.49), large (0.50 - 0.69), very large (0.70 - 0.89), nearly perfect (0.90 - 0.99), and perfect (1.0) (21). Additionally, independent sample T-tests or Mann-Whitney U tests were used for comparisons between 'fast' and 'slow' performers (i.e., fastest ten PTs vs. slowest ten PTs), similar to the procedures of previous research (10,43). Cohen's d effect sizes (*d*) were also implemented to determine the magnitude of differences in performance variables between fast and slow performers. Effect size magnitudes were described based on the following criteria: trivial (< 0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (2.0–4.0) (22). P-values were Bonferroni corrected (i.e., multiplied by number of correlations explored) to avoid family-wise error, with significance set at $p<0.05$ following correction.

RESULTS

Descriptive statistics for each variable are presented in 'Table 2' and 'Table 3'. Performance time demonstrated large significant correlations with peak KAM, horizontal approach velocity, peak KRM, peak KFM ($P < 0.01$), and moderate significant correlations with horizontal exit velocity ($P = 0.007$) and peak hip flexor moment ($P = 0.014$; Table 2). Peak KAM demonstrated large significant correlations with peak hip flexor moment, performance time, peak KFM, peak KRM ($P < 0.01$), and a moderate significant correlation with horizontal approach velocity ($P = 0.015$; Table 2). Peak KRM demonstrated large significant correlations with average ML GRF FFC, average and peak hGRF FFC, horizontal approach velocity, performance time, peak hip flexion moment ($P < 0.01$), and moderate significant correlations with peak KFM, peak KAM, peak ML FFC and peak vGRF FFC ($P < 0.05$; Table 2). Peak KFM showed a moderate significant correlation with peak KAM and peak KRM ($P < 0.01$; Table 2). No significant relationships were found for peak/average HBFR and peak/average hGRF PFC between either PT, peak KAM, peak KRM or peak KFM.

Horizontal exit velocity showed large significant correlations with FFC GCT, LLP distance, peak ML FFC, horizontal approach velocity and average ML FFC ($P < 0.01$) (Table 3). Horizontal approach velocity displayed large significant correlations with average hGRF FFC, horizontal exit velocity, peak hGRF PFC, peak ML FFC, peak hip flexor moment, peak hGRF FFC, and moderate significant correlations with average hGRF PFC ($P = 0.004$) and peak vGRF PFC ($P = 0.013$) (Table 3).

Comparisons between fast and slow performers for performance variables, as well as kinetic and kinematic characteristics are presented in 'Table 4', 'Table 5' and 'Table 6', respectively. Large to very large significant differences between fast and slow performers for performance time ($P < 0.001$; $d = -3.0$), horizontal approach velocity ($P < 0.001$; $d = 2.0$) and horizontal exit velocity ($p = 0.014$; $d = 1.2$) were observed. For the kinetic variables of interest, a large significant difference was observed for peak KRM ($P = 0.005$; $d = -1.7$), and moderate significant differences between fast and slow performers for peak KAM ($P = 0.005$; $d = 1.1$), peak KFM ($P = 0.029$; $d = 1.1$), peak hip flexor moment ($P = 0.016$; $d = -0.9$), and average hGRF PFC ($P = 0.05$; $d = -0.9$) were displayed. Although non-significant ($P > 0.05$), moderate effect sizes were observed for peak hGRF PFC ($d = -0.8$), peak hGRF FFC ($d = -0.7$), average hGRF FFC ($d = -0.8$), peak ML FFC ($d = 0.6$). For the technique variables of interest, only peak KAA was found to be moderately different ($P = 0.042$; $d = -1.0$) between fast and slow performers.

****Insert Table 2 here****

****Insert Table 3 here****

****Insert Table 4 here****

****Insert Table 5 here****

****Insert Table 6 here****

DISCUSSION

The aim of this investigation was to establish whether the technical and mechanical associates of a faster 70-90° cutting maneuver are at odds with the factors responsible for increased multi-planar joint loads at the knee. This study substantiates previous research (17), and further illustrates the conflict between performance and mechanical knee joint loading during cutting. Indeed, peak KAM, KRM and KFM were all significantly related to PT (Table 2) and were also significantly greater for fast performers compared to slow performers (Table 5). Furthermore, horizontal approach and exit velocity, and peak hip flexor moment (FFC) were all variables significantly correlated to faster cutting PTs; however, such variables were also correlated with heightened multi-planar knee joint loading (Table 2). Thus, these findings indicate that the biomechanical characteristics necessary for faster cutting are in direct conflict with those required to reduce knee joint loading and potential ACL strain.

This appears to be first study to conduct a multi-planar biomechanical analysis of knee joint loads during cutting that has been considered from both a performance and injury risk perspective (i.e., increased ACL strain). Previous investigations have typically focused on examining the isolated measure of KAMs in relation to injury risk or performance (5,6,18,24,26,29,40), whereas research which considers multi-planar loading of the knee is somewhat limited (6,24). This type of investigation is certainly warranted based on reports showing that ACL strain is amplified when combined sagittal, frontal and transverse knee moments are generated in contrast to uni-planar loading (38). That there were large to moderate relationships observed between peak KAM, peak KRM and peak KFM (Table 2) consolidates this notion and suggests that the biomechanical factors associated with peak KAMs may likely increase the overall mechanical loading experienced at the knee joint, and thus increased ACL knee injury risk.

Sagittal plane hip mechanics (i.e., peak hip flexor moment, peak KFM) were responsible for faster PTs and greater mechanical knee joint loading (Table 2), and were also significantly different between faster and slower performers (Table 5). This is in contrast the findings of Havens and Sigward (17), who found that frontal plane hip mechanics were performance predictors of a 90° cutting task. It is unclear how increased hip flexor moments would relate to increased knee joint loads, it can only be suggested that faster approach velocities (a correlate of PT, peak KAMs and peak KRMs) into the turn would produce higher GRFs and subsequently greater moments about the hip. Previous work (27,34), however, did find peak hip flexor moments to lower KAMs. The authors suggested (34) that an increased activation of the hip extensor musculature may have enabled a more controlled deceleration into the turn, implicating the role of eccentric strength for deceleration in the sagittal plane prior to direction change in sharper turns (27). Peak KFM was a factor related to both performance and mechanical knee joint loading (Table 2; Table 5) which agrees with the previous work Havens and Sigward (17). From a performance perspective, the knee extensor muscles will act eccentrically to reduce momentum of the system to enable a subsequent rapid transition to reaccelerate into the new intended direction (17). The mechanisms explaining KFM as a potential injury risk factor are less clear, with it being postulated that heightened sagittal knee joint loading may relate to larger shear forces acting on the knee joint during the task (17). It has also been argued that an increased quadriceps activation (i.e., greater peak KFM) may increase the strain on the ACL by increasing the anterior translation at the knee (14); namely, it may be the coupling of this anterior translation produced by the quadriceps with valgus and internal rotation moments that accentuates the loading risk associated with non-contact ACL injury (6), which would support the multi-planar nature of ACL strain injuries (38).

COM horizontal approach and exit velocities were both significantly related to PT, with the former also showing to be associated with knee joint loading (Table 2). High approach velocities have previously been found to contribute to increased KAMs in the FFC (32,46), which would be expected based on the increasingly higher forces that are generated with increased running velocities (46). Furthermore, higher velocities (27), peak accelerations and peak speeds during COD tasks of 45° and 90° have all been previously shown to determine COD performance (16). It is unsurprising that high running velocities corresponded with improved PTs, given that faster speeds equate to distances being covered in shorter time. These results, however, do add emphasis to the 'performance-injury risk' conflict apparent in cutting, as faster athletes experience greater loads, and thus potentially ACL strain. Accordingly, practitioners should aim to improve the approach velocities of athletes but acknowledge the concurrent increased knee joint loading that may coincide with these improvements.

In contrast to the work of Havens and Sigward (17) that only examined PT, the present study investigated the COM velocity during the approach and exit, which allowed for a COD velocity profile to be examined (16). As such, LLP distance, peak and average ML FFC, and horizontal approach velocity were all correlated with horizontal exit velocity (Table 3). LLP distance has been identified as a determinant of peak KAMs (5,6,17,26) and also as a performance determinant (17,23). When the foot is placed laterally further from the midline of the body during FFC, this causes the center of pressure to be positioned more laterally to the knee joint axis, thereby creating a larger moment arm for the intersegmental GRFs to act and subsequently amplify the KAMs sustained at the knee joint (17,40). This lateral translation will also act to accelerate the COM to the contralateral side (33), thus highlighting LLP as a correlate of performance. Practitioners should apply caution when modifying lateral foot plant distances to reduce injury risk (i.e., coaching a more medially oriented foot placement) (5,6), as athletes are less likely to adopt technique that puts constraints on performance.

The finding that both peak and average ML GRFs related to horizontal exit velocity may be explained by the mechanical principle which states that direction change is most effectively achieved when force is applied perpendicular to current direction of motion (30). Thus, a large ML GRF, generated with a large LLP distance, will maximize the frictional force applied and resultant exit velocity directed towards the intended direction of travel (40). Although the application of GRFs as performance (10,18,41–43) and injury risk (25,39,40) factors have been well documented, this study is one of only another (17) to have considered from a performance perspective the technical elements alongside GRF application which are required during different COD tasks. Larger horizontal propulsive forces have been previously shown to contribute to performance of a 180° pivoting maneuver (10), with the authors suggesting that athletes who apply horizontal forces more effectively are able to propel themselves into the new intended direction at higher velocities. Although different tasks were performed (i.e., 70-90° cut vs. 180° pivot), comparisons can still be made when the direction of travel is assessed in its mechanical terms; the dominant anterior-posterior kinetics during a 180° pivot may shift towards an increased demand on ML kinetics of the

70-90° cut. Therefore, it may be stipulated that athletes who elicit higher ML GRFs in the FFC enable greater propulsion into a more laterally directed exit (i.e., 70-90° cut) (23).

A number of GRF FFC properties were associated with peak KRM (Table 2) and, although non-significant, displayed small to moderate effect sizes between fast and slow performers (Table 5). These findings are in agreement with previous findings by Jones *et al.* (25) of a similar cutting angle that found horizontal GRF FFC properties were related to peak KAMs. This would be expected as heightened GRFs generated during FFC would correspond with increased overall mechanical loading at the knee (25,26,39). However, no relationships were found between any GRF PFC variables and mechanical knee joint loading, which is in contrast to the findings mentioned above (25). On the surface, this suggests that the braking characteristics in the PFC are not as important as previously suggested, which is perhaps surprising, considering COD tasks of a sharper nature (i.e., > 45°) have been shown to necessitate its role (10,27). It is worth noting, however, a moderate effect size for average hGRF PFC and a moderate yet non-significant effect size for peak hGRF PFC was observed between fast and slower performers (Table 5), which may provide some evidence for this braking strategy. Additionally, it should be acknowledged that the distance of this present study was notably shorter than used previously (i.e., 5 m vs. 10, 15 m), which has been shown to influence the involvement of braking characteristics in respective tasks (28). Furthermore, it cannot be dismissed that the reduced cutting angle undertaken in this investigation may have altered the braking kinetics demonstrated in the PFC, as shallower cutting angles may require lower reductions in momentum (achieved partly via greater hGRFs) before re-accelerating out of the turn (9,25). It has been stipulated that, during the PFC, GRFs are dissipated through flexion of the hip and knee joints (25,32), which occurs throughout the entire stance phase and through transition into the FFC. Resultantly, the participant's COM is lowered and the right leg can be planted in front of the body (i.e., increasing the hGRF directed vector) (25). This PFC braking strategy may be useful from both performance and injury risk perspectives, as not only does the reduction in GRFs in the FFC subsequently reduce the peak KAMs experienced, but it also means less momentum needs to be dissipated during the FFC, which may reduce GCT during the FFC and allow for more rapid extension of the joints for propulsion out of the turn (10,19). This may explain the relationship observed between GCT FFC and exit velocity (Table 3), as well as the moderate, albeit non-significant, effect sizes observed between faster and slower performers (Table 5). These findings substantiate previous research which has suggested that shorter GCT FFC are factors of COD performance (10,18,41–43).

Interestingly, other than LLP distance, no technique variables had meaningful significant correlations with performance factors (PT/exit velocity) or peak KAMs. An explanation may be that the mechanical characteristics of the task play more importance over the technical characteristics, which partly explains the high contributions that velocity and kinetic variables had to both PTs and peak KAMs. This would point towards the physical condition of the participants being the key factor when assessing COD ability, and that possibly, for well-trained athletes, such as recruited in this present study, the importance of technique development may play a subordinate role to developing the overall physical capacity to tolerate the demands of COD. More comprehensive investigations (i.e., kinetic and kinematic analyses) into the differences between ‘stronger’ and ‘weaker’ athletes should be considered to determine whether this is the case.

Although this present study provides more insight into the kinetic and kinematic determinants of cutting from both performance and injury risk standpoints, there are still certain limitations that need to be addressed before more clarity on the topic is accomplished. For example, it was beyond the scope of this current investigation to examine preparatory trunk characteristics, given that our rationale was to develop on previous work (10,25,26) that has focused purely on the braking characteristics in the PFC. How much 'pre-rotation' occurs during the PFC is an area that needs to be further explored to provide more clarity on the role of the steps preceding FFC and may further elucidate the 'multi-step' nature of COD actions. Another limitation is that trials were limited to performing the cutting maneuver on the right limb (push-off) due to the lab configuration. That being said, it has been shown that only subtle differences in COD biomechanics exist between limbs (13) and so it is argued that informed conclusions for both limbs can still be made from these findings.

PRACTICAL APPLICATIONS

In light of these current findings, it must be acknowledged that cutting programs that emphasize instruction to improve performance come with the inherent risk of increased knee joint loading of cuts from 70-90° cut. The fundamental issue here is that athletes that are driven by peak performance are unlikely to adhere to injury risk mitigation strategies that may compromise their ability to execute movements to the highest level. Therefore, we recommend that practitioners are advised to program accordingly, with a primary aim being to improve the lower-body strength capacity of the athlete (i.e., concentric, eccentric, isometric, reactive) and develop the ability to apply these qualities impulsively over short GCT's (i.e., rate of force development). The technique cues that have been proven to reduce knee joint loading may be beneficial for athletes that do not display adequate strength levels, and can be subsequently reviewed once they are sufficient. An example here could be that coaching a large LLP may in fact be beneficial for an athlete who can tolerate the increased knee joint loading; however, an individual who demonstrates strength deficits may benefit more from targeted strength training, from which they are coached to express these developing qualities within ‘lower risk’ postures (i.e., reduced LLP). This suggestion may enable practitioners and athletes to optimize the ‘performance-injury risk’ trade-off within the context of the individual’s needs. Coaches and practitioners should also be aware of the role of the PFC during turns of sharper angles and of higher approach velocities and deliver cues according to how sharp the cutting task at hand may be. These recommendations should facilitate the coaching of joint positions and moments that are advantageous to performance to be reinforced, without any concurrent movement breakdown of the athlete through inadequate physical capacity.

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Figure

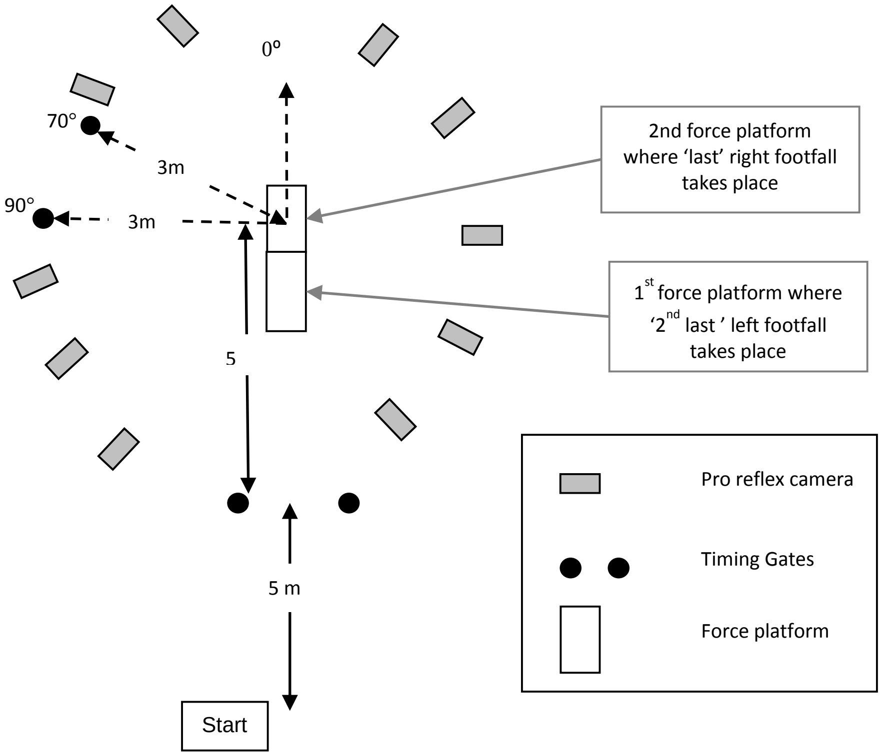

Figure 1. Plan visualization of experimental set-up.

Table 1. Biomechanical variables of interest with definitions.

Variable	Abbreviation	Definition
Independent Variables		
Performance time (s)	-	Time to complete cutting task
Peak external knee abduction moment ($Nm \cdot kg^{-1}$)	Peak KAM	Peak KAM (+ abduction/- adduction) during weight acceptance phase of FFC using inverse dynamics
Peak external knee rotation moment ($Nm \cdot kg^{-1}$)	Peak KRM	Peak KRM during weight acceptance phase of FFC using inverse dynamics
Peak external knee flexion moment ($Nm \cdot kg^{-1}$)	Peak KFM	Peak KFM during weight acceptance phase of FFC using inverse dynamics
Dependent Variables		
Performance Characteristics		
Horizontal approach velocity ($m \cdot s^{-1}$)	-	Model COM position was determined from 10 frames prior to PFC to 10 frames from the toe-off of the FFC. The first derivative of the model COM position was computed to derive anterior-posterior (x), vertical (z) and medial-lateral (y) velocity over this period. Resultant horizontal plane velocity ($\sqrt{}$ ((COM vel $(x)^2$) + (COM vel $(y)^2$)) was subsequently calculated to provide a 'velocity

		profile' along the path of the subject's COM during the cutting maneuver. Resultant horizontal plane velocity at the start of PFC was determined to represent the horizontal approach velocity of the participant for that trial	
Horizontal exit velocity ($m \cdot s^{-1}$)	-	Resultant horizontal plane velocity at take-off of the final foot contact	
Kinetic Characteristics		***Peak***	***Average***
Penultimate horizontal ground reaction force ($N \cdot kg^{-1}$)	hGRF PFC	Normalized peak hGRF during weight acceptance phase of PFC	Normalized average hGRF during weight acceptance phase of PFC
Final horizontal ground reaction force ($N \cdot kg^{-1}$)	hGRF FFC	Normalized peak hGRF during weight acceptance phase of FFC	Normalized average hGRF during weight acceptance phase of FFC
Penultimate vertical ground reaction force ($N \cdot kg^{-1}$)	vGRF PFC	Normalized peak vGRF during weight acceptance phase of PFC	Normalized average vGRF during weight acceptance phase of PFC
Final vertical ground reaction force ($N \cdot kg^{-1}$)	vGRF FFC	Normalized peak vGRF during weight acceptance phase of FFC	Normalized average vGRF during weight acceptance phase of FFC
Final medial-lateral	ML GRF FFC	Normalized peak ML	Normalized average ML

propulsive force (N·kg^{-1})		GRF during propulsion phase of FFC	GRF during propulsion phase of FFC
Horizontal braking force ratio	HBFR	Peak hGRF FFC divided by peak hGRF PFC	Average hGRF FFC divided by peak hGRF PFC
Penultimate ground contact time (s)	PFC GCT	The instant after ground contact of PFC in which the vGRF was higher than 20 N and the point where the vGRF subsided past 20 N (end of contact)	
Final ground contact time (s)	FFC GCT	The instant after ground contact of FFC in which the vGRF was higher than 20 N and the point where the vGRF subsided past 20 N (end of contact)	
Peak sagittal plane hip, knee and ankle moments (Nm·kg^{-1})	-	Peak external joint moments during weight acceptance and propulsion phase of FFC using inverse dynamics	
Kinematic Characteristics			
Peak hip, knee and ankle joint flexion angles (°)	-	Derived from the following order of rotations: flexion (+)	
Right knee adduction angle (°)	KAA	Maximum knee adduction angle (-) during weight acceptance phase of FFC	
Lateral leg plant distance	LLP	Lateral distance from COM of the plant foot at	

(m)		initial foot contact of foot to proximal end of the pelvis (relative to the frontal plane)
Lateral trunk flexion angle (°)	-	Angle of the trunk in the frontal plane relative to a vertical line in the lab co-ordinate system: upright (0)/trunk flexion away from plant leg (+)/trunk flexion towards plant leg (-)
Initial foot progression angle (°)	-	Angle of foot progression relative to original direction: straight (0)/inward rotation (+)/outward rotation (-)
'True' cut angle (°)	-	Actual angle of cut that was performed during the intended 70-90° COD task. Calculated using the following: tan (y velocity component at take-off/ x velocity component at take-off)

Key: COM = center of mass; COD = change of direction.

Table 2

Table 2. Descriptive statistics and correlation values for variables with large and moderate associations with performance time and multi-planar knee joint loading.

	Mean ± SD	R or ρ	P
Performance time (s) #	2.07 ± 0.13	-	-
Peak KAM (Nm·kg^{-1})	1.04 ± 0.73	- 0.590	<0.001
Horizontal approach velocity (m·s^{-1})	4.29 ± 0.31	- 0.579	<0.001
Peak KRM (Nm·kg^{-1})	-0.76 ± 0.36	0.525	0.001
Peak KFM (Nm·kg^{-1})	2.96 ± 0.72	- 0.509	0.002
Horizontal exit velocity (m·s^{-1})	3.30 ± 0.25	-0.451	0.007
Peak hip flexor moment FFC (Nm·kg^{-1})	- 3.50 ± 1.77	0.418	0.014
Peak knee abduction moment (Nm·kg^{-1}) #	1.04 ± 0.73	-	-
Peak hip flexor moment FFC (Nm·kg^{-1})	- 3.50 ± 1.77	-0.624	<0.001
Performance time (s)	2.07 ± 0.13	-0.590	<0.001
Peak KFM (Nm·kg^{-1})	2.96 ± 0.72	0.549	0.002
Peak KRM (Nm·kg^{-1})	-0.76 ± 0.36	-0.488	0.003
Horizontal approach velocity (m·s^{-1})	4.29 0.31	0.414	0.015
Peak knee rotation moment (Nm·kg^{-1})	-0.76 ± 0.36	-	-
Average ML FFC (N·kg^{-1})	0.66 ± 0.17	-0.638	<0.001
Average hGRF FFC (N·kg^{-1})	-0.81 ± 0.17	0.581	<0.001
Peak hGRF FFC (N·kg^{-1})	-1.38 ± 0.33	0.576	<0.001
Horizontal approach velocity (m·s^{-1})	4.29 0.31	-0.568	<0.001
Performance time (s) #	2.07 ± 0.13	0.525	0.001
Peak hip flexor moment FFC (Nm·kg^{-1}) #	-3.50 ± 1.77	0.517	0.002
Peak KFM (Nm·kg^{-1})	2.96 ± 0.72	-0.494	0.003
Peak KAM (Nm·kg^{-1})	1.04 ± 0.73	-0.488	0.003
Peak ML FFC (N·kg^{-1})	1.18 ± 0.33	-0.430	0.011
Peak vGRF FFC (N·kg^{-1})	-1.39 ± 0.40	-0.412	0.016
Peak knee flexion moment (Nm·kg^{-1})	2.96 ± 0.72	-	-

Peak KAM ($Nm \cdot kg^{-1}$)	2.96 ± 0.72	- 0.549	0.002
Performance time (s)	2.96 ± 0.72	- 0.509	0.002
Peak KRM ($Nm \cdot kg^{-1}$)	-0.76 ± 0.36	-0.494	0.003

Key: # = Spearman's correlation coefficient; SD = standard deviation; FFC = final foot contact; KAM = knee abduction moment; KRM = knee rotation moment; KFM = knee flexion moment; ML = medial-lateral.

Table 3

Table 3. Descriptive statistics and Pearson's correlation for variables large and moderate associations with exit velocity and approach velocity.

	Mean ± SD	**R or ρ**	**P**
Horizontal exit velocity (m·s^{-1})	3.30 ± 0.25	-	-
GCT FFC (s)	0.31 ± 0.05	- 0.590	<0.001
Lateral leg plant distance (m)	- 0.31 ± 0.05	- 0.582	0.001
Peak ML propulsive force (N·kg^{-1})	1.18 ± 0.33	0.570	<0.001
Horizontal approach velocity (m·s^{-1})	4.29 ± 0.31	0.562	0.001
Average ML propulsive force (N·kg^{-1})	0.66 ± 0.17	0.512	0.002
Horizontal approach velocity (m·s^{-1})	4.29 ± 0.31	-	-
Average hGRF FFC (N·kg^{-1})	- 0.81 ± 0.17	- 0.622	<0.001
Peak KAM (Nm·kg^{-1}) #	1.04 ± 0.73	- 0.590	<0.001
Peak KRM (Nm·kg^{-1})	2.96 ± 0.72	-0.568	<0.001
Peak hGRF PFC (N·kg^{-1})	- 1.39 ± 0.40	- 0.548	0.001
Peak ML propulsive force (N·kg^{-1})	1.18 ± 0.33	0.520	0.002
Peak hip extensor moment FFC (Nm·kg^{-1}) #	- 3.50 ± 1.77	0.511	0.002
Peak hGRF force FFC (N·kg^{-1})	- 1.38 ± 0.33	- 0.492	0.003
Average hGRF force PFC (N·kg^{-1})	- 0.54 ± 0.09	- 0.478	0.004
Peak vGRF PFC (N·kg^{-1}) #	2.54 ± 0.56	0.423	0.013

Key: # = Spearman's correlation coefficient; SD = standard deviation; ML = medial-lateral; FFC = final foot contact; KAM = knee abduction moment; KRM = knee rotation moment; PFC = penultimate foot contact; vGRF = vertical ground reaction force; hGRF = horizontal ground reaction force.

Table 4

Table 4. Performance characteristic comparisons between fast and slow performers.

Variable	Fast (n = 10)	Slow (n = 10)	P-value	*d*	CI (95%)		Descriptor
Performance variable					*LB*	*UB*	
Performance time (s) #	1.95 ± 0.06	2.20 ± 0.10	<0.001	- 3.0	- 1.7	- 4.4	Very large
Horizonal approach velocity ($m \cdot s^{-1}$)	4.58 ± 0.20	4.08 ± 0.28	<0.001	2.0	1.0	3.1	Very large
Horizontal exit velocity ($m \cdot s^{-1}$)	3.48 ± 0.17	3.20 ± 0.28	0.014	1.2	0.3	2.2	Large

Key: # = Kruskal–Wallis H test; *d* = Cohen's *d* effect size; CI = 95% confidence interval; LB = lower bound 95% confidence interval; UB = upper bound 95% confidence interval.

Table 5

Table 5. Kinetic characteristic comparisons between fast and slow performers.

Variable	Fast (n = 10)	Slow (n = 10)	P-value	*d*	CI (95%)		Descriptor
GRF Properties					*LB*	*UB*	
Peak vGRF PFC (N·kg^{-1})	2.72 ± 0.61	2.41 ± 0.54	0.248	0.5	- 0.4	1.4	Small
Peak hGRF PFC (N·kg^{-1})	- 1.57 ± 0.39	- 1.24 ± 0.45	0.097	-0.8	- 1.7	0.1	Moderate
Average hGRF PFC (N·kg^{-1})	-0.57 ± 0.072	- 0.49 ± 0.10	0.050	-0.9	- 1.9	0.0	Moderate
Peak vGRF FFC (N·kg^{-1})	2.65 ± 0.42	2.54 ± 0.530	0.616	0.2	- 0.7	1.1	Small
Peak hGRF FFC (N·kg^{-1})	- 1.47 ± 0.29	- 1.28 ± 0.22	0.127	-0.7	- 1.6	0.2	Moderate
Average hGRF FFC (N·kg^{-1})	- 0.90 ± 0.16	- 0.78 ± 0.15	0.087	-0.8	- 1.7	0.1	Moderate
Peak HBFR	1.10 ± 0.29	1.01 ± 0.44	0.595	0.2	- 0.6	1.1	Small
Average HBFR #	1.60 ± 0.30	1.68 ± 0.67	0.705	-0.2	- 1.0	0.7	Small
Peak ML propulsive force FFC (N·kg^{-1})	1.32 ± 0.32	1.11 ± 0.35	0.176	0.6	- 0.3	1.5	Moderate
Average ML propulsive force FFC (N·kg^{-1})	0.71 ± 0.18	0.65 ± 0.17	0.481	0.3	- 0.6	1.2	Small
GCT PFC (s)	0.19 ± 0.03	0.20 ± 0.04	0.357	- 0.4	- 0.5	- 0.2	Small
GCT FFC (s)	0.29 ± 0.04	0.33 ± 0.06	0.123	- 0.7	- 0.6	- 0.1	Moderate
Moments							
Peak KAM (Nm·kg^{-1}) #	1.62 ± 1.14	0.70 ± 0.18	0.005	1.1	0.2	2.1	Moderate
Peak KRM (Nm·kg^{-1}) #	-1.01 ± 0.34	-0.54 ± 0.18	0.005	-1.7	- 2.7	- 0.7	Large
Peak right hip flexor moment (Nm·kg^{-1}) #	- 4.44 ± 2.35	- 2.77 ± 0.95	0.016	- 0.9	- 1.8	0.0	Moderate
Peak KFM (Nm·kg^{-1})	3.46 ± 0.72	2.68 ± 0.75	0.029	1.1	0.1	2.0	Moderate
Peak right ankle dorsi-flexor moment (Nm·kg^{-1})	- 1.53 ± 0.82	- 1.37 ± 0.50	0.624	- 0.2	- 1.1	0.7	Small
Peak left hip flexor moment (Nm·kg^{-1}) #	1.76 ± 0.62	3.21 ± 4.15	0.326	- 0.5	- 1.4	0.4	Small
Peak left knee flexor moment (Nm·kg^{-1}) #	3.26 ± 0.60	3.17 ± 1.53	0.257	0.1	- 0.8	1.0	Trivial
Peak left ankle dorsi-flexor moment (Nm·kg^{-1}) #	- 0.66 ± 0.15	- 0.80 ± 0.42	0.545	0.4	- 0.4	1.3	Small

Key: # = Kruskal–Wallis H test; *d* = Cohen's *d* effect size; CI = 95% confidence interval; GRF = ground reaction force; LB = lower bound 95% confidence interval; UB = upper bound 95% confidence interval; vGRF = vertical ground reaction force; PFC = penultimate foot contact; hGRF = horizontal ground reaction force; FFC = final foot contact; HBFR = horizontal braking force ratio; ML = medial-lateral; GCT = ground contact time; KAM = knee abduction moment; KRM = knee rotation moment; KFM = knee flexion moment.

Table 6

Table 6. Kinematic characteristic comparisons between fast and slow performers.

Variable	Fast (n = 10)	Slow (n = 10)	P-value	*d*	CI (95%)		Descriptor
Technique					*LB*	*UB*	
Peak KAA (°)	- 12.08 ± 5.54	- 6.94 ± 4.96	0.042	- 1.0	- 1.9	- 0.1	Moderate
LLP distance (m)	- 0.34 ± 0.07	- 0.31 ± 0.05	0.302	-0.5	- 1.4	0.4	Small
Lateral trunk flexion angle (°)	- 20.14 ± 4.56	- 21.22 ± 8.55	0.743	0.2	- 0.7	1.0	Small
Initial foot progression angle (°) #	8.36 ± 34.96	14.09 ± 4.69	0.895	-0.2	- 1.1	0.6	Small

Key: # = Kruskal–Wallis H test *d* = Cohen's *d* effect size; CI = 95% confidence interval; LB = lower bound 95% confidence interval; UB = upper bound 95% confidence interval; KAM = knee adduction moment; KAA = knee adduction angle; LLP = lateral leg plant. All reported values are with respect to final foot contact.