Physical Therapy in Sport 38 (2019) 152–161

Contents lists available at ScienceDirect

Physical Therapy in Sport

journal homepage: www.elsevier.com/ptsp

Original Research

A qualitative screening tool to identify athletes with 'high-risk' movement mechanics during cutting: The cutting movement assessment score (CMAS)

Thomas Dos'Santos [a, *], Alistair McBurnie [a], Thomas Donelon [b], Christopher Thomas [a], Paul Comfort [a], Paul A. Jones [a]

[a] Human Performance Laboratory, Directorate of Sport, Exercise, and Physiotherapy, University of Salford, Greater Manchester, United Kingdom
[b] Section of Sport and Exercise Sciences, Canterbury Christ Church University, Kent, United Kingdom

ARTICLE INFO

Article history:
Received 5 March 2019
Received in revised form
7 May 2019
Accepted 20 May 2019

Keywords:
Anterior cruciate ligament
Knee abduction moment
Injury screening
Injury-risk profile

ABSTRACT

Objective: To assess the validity of the cutting movement assessment score (CMAS) to estimate the magnitude of peak knee abduction moments (KAM) against three-dimensional (3D) motion analysis, while comparing whole-body kinetics and kinematics between subjects of low (bottom 33%) and high CMASs (top 33%).
Design: Cross-sectional study.
Setting: Laboratory.
Participants: Forty-one participants (soccer, rugby, netball, and cricket).
Main outcome measures: Association between peak KAM and CMAS during a 90° cut. Comparison of 3D whole-body kinetics and kinematics between subjects with low (bottom 33%) and high CMASs (top 33%).
Results: A very large significant relationship ($\rho = 0.796$, $p < 0.001$) between CMAS and peak KAM was observed. Subjects with higher CMASs displayed higher-risk cutting postures, including greater peak knee abduction angles, internal foot progression angles, and lateral foot plant distances ($p \leq 0.032$, effect size = 0.83–1.64). Additionally, greater cutting multiplanar knee joint loads (knee flexion, internal rotation, and abduction moments) were demonstrated by subjects with higher CMASs compared to lower ($p \leq 0.047$, effect size = 0.77–2.24).
Conclusion: The CMAS is a valid qualitative screening tool for evaluating cutting movement quality and is therefore a potential method to identify athletes who generate high KAMs and "high-risk" side-step cutting mechanics.

1. Introduction

Side-step lateral foot plant-and-cut actions are frequently performed movements in numerous sports (Fox, Spittle, Otago, & Saunders, 2014; Wheeler, Askew, & Sayers, 2010) and are also linked to decisive moments in matches, such as evading an opponent to penetrate the defensive line in rugby (tackle-break success in rugby) (Wheeler et al., 2010), or getting into space to receive a pass in netball (Fox et al., 2014). Side-step cutting, however, are also actions associated with non-contact anterior cruciate ligament (ACL) injuries in sports (Johnston et al., 2018; Koga et al., 2010). Although ACL injury-risk factors are multifactorial (Quatman, Quatman-Yates, & Hewett, 2010) and a complex interaction of internal and external factors (i.e. anatomical, hormonal, environmental, shoe-surface interface, anticipation, and fatigue) (Bittencourt et al., 2016; Hewett, 2017; Krosshaug et al., 2007b), a large proportion of ACL injuries are non-contact in nature during high velocity and impact sporting tasks, such as side-stepping (Boden, Dean, Feagin, & Garrett, 2000; Johnston et al., 2018; Krosshaug et al., 2007b). This occurrence can be attributed to the tendency to generate large multiplanar knee joint loading, such as knee abduction moments (KAM) and internal rotation moments (KIRM) (Besier, Lloyd, Cochrane, & Ackland, 2001; Dempsey et al., 2007; Jones, Herrington, & Graham-Smith, 2016a), which increase ACL strain (Bates, Myer, Shearn, & Hewett, 2015; Markolf et al.,

* Corresponding author. Allerton Building, Frederick Road Campus, Salford, Greater Manchester, M6 6PU, United Kingdom.
E-mail address: t.dossantos@edu.salford.ac.uk (T. Dos'Santos).

https://doi.org/10.1016/j.ptsp.2019.05.004
1466-853X/

1995; Shin, Chaudhari, & Andriacchi, 2011). These potentially hazardous knee joint loads are amplified when poor initial postures and movement is demonstrated (biomechanical and neuromuscular control deficits) during cutting (Fox, 2018; Hewett, 2017; Myer, Brent, Ford, & Hewett, 2011), but importantly these deficits are modifiable (Hewett, 2017; Padua et al., 2018). As such, understanding the mechanics, interventions, and screening tools that can reduce ACL injury-risk factors is of critical importance.

The ability to identify athletes potentially at risk of injury is a critical step in effective ACL injury-risk reduction (Fox, Bonacci, McLean, & Saunders, 2017; Hewett, 2017). Although it is inconclusive whether screening tools can predict non-contact ACL injury (Bahr, 2016; Fox, Bonacci, McLean, Spittle, & Saunders, 2015), evaluating movement quality and identifying biomechanical and neuromuscular control deficits (high-risk movement patterns) can provide important information regarding an athlete's "injury-risk profile" (Herrington, Munro, & Jones, 2018; McCunn & Meyer, 2016; Mok & Leow, 2016). These abnormal deficits include knee abduction angles (KAA) (Jones et al., 2015, 2016b; Kristianslund, Faul, Bahr, Myklebust, & Krosshaug, 2014; McLean, Huang, & van den Bogert, 2005; Sigward, Cesar, & Havens, 2015), lateral trunk flexion (Dempsey et al., 2007; Frank et al., 2013; Jamison, Pan, & Chaudhari, 2012; Jones et al., 2015), extended knee postures (Dai et al., 2014; Koga et al., 2010; Weir, Alderson, Smailes, Elliott, & Donnelly, 2019), and hip internal rotation (Havens & Sigward, 2015; McLean et al., 2005; Sigward et al., 2015; Sigward & Powers, 2007). This information from movement screening can subsequently be used to inform the future prescription of training and conditioning so specific deficits can be targeted through appropriate training interventions to decrease the relative risk of injury (Herrington et al., 2018; Hewett, 2016; Mok & Leow, 2016). Therefore, the inclusion of valid and reliable screening tools that assess movement quality are an important component of sports medicine and strength and conditioning testing batteries to provide an "injury-risk profile" for an athlete (Herrington et al., 2018; Jones, Donelon, & Dos' Santos, 2017).

Three-dimensional (3D) motion analysis is considered the gold standard for evaluating movement kinetics and kinematics (Fox et al., 2015; Hewett, 2017); however, this method can be susceptible to errors, with a diverse range of data collection and analysis procedures available to practitioners which can impact outcome values, reliability, or subsequent evaluations of an athlete's biomechanical profile (Camomilla et al., 2017; Kristianslund, Krosshaug, & van den Bogert, 2012). Given these methodological considerations and issues, and the fact the 3D motion analysis is expensive, time-consuming, requires expert and well trained assessors, and is usually restricted to testing one subject in laboratory setting, time- and cost-effective qualitative field-based screening tools have been developed, such as the landing error scoring system (LESS) (Padua et al., 2009, 2011), tuck jump assessment (TJA) (Herrington, Myer, & Munro, 2013; Myer, Ford, & Hewett, 2008), and qualitative analysis of single leg loading (QASLS) (Almangoush, Herrington, & Jones, 2014; Herrington et al., 2013), to assess lower-limb and whole-body postures associated with increased potential risk of injury (high-risk movement patterns). However, the LESS is the only screening tool of that has been validated against 3D motion analysis (Onate, Cortes, Welch, & Van Lunen, 2010; Padua et al., 2009).

A fundamental shortcoming of the LESS, TJA, and QASLS are these assessments generally assess landing mechanics during a vertical-orientated task. Although screening landing mechanics is indeed applicable to jump-landing sports (netball, basketball, volleyball) where the primary action associated with non-contact ACL injury is landing manoeuvres (Hewett, Torg, & Boden, 2009; Krosshaug et al., 2007b; Stuelcken, Mellifont, Gorman, & Sayers, 2016), these aforementioned assessments may lack specificity to the unilateral, multiplanar plant-and-cut manoeuvres observed when changing direction (Fox et al., 2015; Jones et al., 2017b; Mok & Leow, 2016). This is particularly important when aiming to screen athletes who participate in sports such as soccer (Walden et al., 2015), handball (Olsen, Myklebust, Engebretsen, & Bahr, 2004), American football (Johnston et al., 2018), badminton (Kimura et al., 2010), and rugby (Montgomery et al., 2018), where directional changes are a primary action associated with-non contact ACL injuries. Furthermore, there are mixed findings whether examination of landing mechanics can identify athletes with poor cutting mechanics (Alenezi, Herrington, Jones, & Jones, 2014; Chinnasee, Weir, Sasimontonkul, Alderson, & Donnelly, 2018; Kristianslund & Krosshaug, 2013; O'Connor, Monteiro, & Hoelker, 2009), with evidence suggesting an athlete's mechanics and "injury-risk profile" are task dependent (Chinnasee et al., 2018; Jones, Herrington, Munro, & Graham-Smith, 2014; Kristianslund & Krosshaug, 2013; Munro, Herrington, & Comfort, 2017). As such, screening side-step cutting technique, which is specific to the actions associated with non-contact ACL injuries in cutting sports (i.e. rugby, handball, soccer, American football), could be a more effective strategy for identifying poor cutting movement quality in athletes, which can help inform future injury-risk mitigation training.

Unfortunately, there is a paucity of field-based cutting screening tools available for practitioners. McLean et al. (McLean et al., 2005) initially evaluated two-dimensional (2D) estimates of frontal plane knee motion during cutting against the gold standard of 3D, and found 2D estimates correlated well with side-step ($r^2 = 0.58$) and side-jump ($r^2 = 0.64$) 3D valgus angles, but poorer associations were observed with 180° turn knee valgus angle ($r^2 = 0.04$); thus, highlighting the difficulty in assessing 2D valgus motion in the frontal plane using a single camera during sharp CODs. Weir et al. (Weir et al., 2019) has recently demonstrated that 2D measures of dynamic knee valgus angle, knee flexion angle at foot-strike and ROM, trunk flexion ROM, when inserted in regression equations, can be used to predict 3D peak knee flexor, KAM and KIRMs during unanticipated side-steps. Despite these promising relationships, such 2D side-step screening methods are not widely adopted by practitioners and clinicians. This lack of adoption could be attributed to the 2D method requiring additional time and software to measure joint kinematics, thus potentially limiting its applicability in field settings.

In light of the issues associated with 2D analysis, Jones et al. (Jones et al., 2017) have recently developed the cutting movement assessment score (CMAS), which is a qualitative screening tool that assesses cutting movement quality and specific lower-limb and trunk characteristics that are associated with (Fox, 2018; Kristianslund et al., 2014; Weir et al., 2019) peak KAMs (Supplement 1), such as penultimate foot contact (PFC) braking strategy, and trunk, hip, knee, and foot positioning and motions. In this preliminary study, a strong relationship between CMAS and peak KAM ($\rho = 0.633$; $p < 0.001$) was demonstrated, while moderate to excellent intra-and inter-rater agreements for all CMAS variables (Intra-rater: $k = 0.60$–1.00, 75–100% agreements; inter-rater: $k = 0.71$–1.00, 87.5–100% agreements) were observed, although lower inter-rater agreements for trunk positioning were observed ($k = 0.40$, 62.5% agreement). In light of these findings, the CMAS may have the potential to identify athletes displaying "high-risk" cutting mechanics but more importantly, could be used as a technical framework for coaching safer cutting mechanics. It should be noted, however, that the preliminary study contained a small sample size (n = 8 subjects, 36 trials) and must be expanded with a greater sample size to confirm its validity and reliability. Furthermore, the authors recommended an additional camera to be placed at 45° relative to the COD and using a higher video capture rate

(≥100 Hz) to permit more accurate and reliable assessments for frontal and transverse plane technique deficits (i.e. trunk positioning, knee valgus).

The aim of this study, therefore, was to assess the validity of the CMAS tool to estimate the potential peak KAMs against the gold standard of 3D motion analysis, expanding on the work of Jones et al. (Jones et al., 2017) by examining a larger sample size and using an additional camera recording at a higher sampling rate. A further aim to was to determine whether "higher-risk" movement mechanics were displayed by subjects with higher CMASs compared to subjects with lower CMASs. Firstly, it was hypothesised that excellent inter- and intra-rater reliability would be demonstrated for CMAS items. Secondly, in line with Jones et al. (Jones et al., 2017), it was hypothesised that a strong relationship would be demonstrated between CMAS and peak KAM, and the CMAS would be able to discriminate between "low" and "high" CMASs in terms of "high-risk" whole-body kinetics and kinematics.

2. Methods

2.1. Experimental approach

This study used a cross-sectional design to determine the relationship between CMAS and peak KAMs during cutting over one session. Participants performed six 90° cuts (70–90°) whereby 3D motion and 2D video footage data were simultaneously captured to permit qualitative screening and comparisons to 3D motion data, similar to the procedures of previous research (Jones et al., 2017; Padua et al., 2009).

2.2. Participants

Based on the work of Jones et al. (Jones et al., 2017) who determined the relationship between CMAS and peak KAM, a minimum sample size of 29 was determined from an *a priori* power analysis using G*Power (Version 3.1, University of Dusseldorf, Germany) (Faul, Erdfelder, Buchner, & Lang, 2009). This was based upon a correlation value of $\rho = 0.633$, a power of 0.95, and type 1 error or alpha level of 0.05. As such, 41 athletes (28 males/13 females) from multiple sports (soccer, rugby, netball, and cricket) (mean ± SD; age: 21.3 ± 4.0 years, height: 1.75 ± 0.08 m, mass: 72.8 ± 11.8 kg) participated in this study. For inclusion in the study, all athletes had played their respective sport for a minimum of 5 years and regularly participated in one game and performed two structured skill-based training sessions per week. All athletes were free from injury and had never suffered a prior traumatic knee injury such as an ACL injury. At the time of testing, players were currently in-season (competition phase). The investigation was approved by the institutional ethics review board, and all participants were informed of the benefits and risks of the investigation prior to signing an institutionally approved consent and parental assent documents to participate in the study.

2.3. Cutting movement assessment score

Table 1 presents the CMAS qualitative screening analysis tool to estimate the magnitude of KAMs during cutting, which has been slightly modified from the preliminary investigation by Jones et al. (Jones et al., 2017) (i.e. extra description provided to some criteria). The CMAS is based on research pertaining to technical determinants of peak KAMs during 30–90° side-step cutting (Fox, 2018; Kristianslund et al., 2014; Weir et al., 2019) and visual observations of non-contact ACL injuries (Johnston et al., 2018; Koga et al., 2010; Olsen et al., 2004). Supplement 1 contains operational definitions and a biomechanical rationale of the CMAS. If an athlete exhibits any of the characteristics in Table 1 they are awarded a score, with a higher score representative of poorer technique and potentially greater peak KAM (Jones et al., 2017).

2.4. Procedures

The warm up, 90° cut (Dos'Santos, Comfort, & Jones, 2018), marker placement (Dos'Santos et al., 2018; Jones et al., 2016a; Jones et al., 2017), and 3D motion analysis (Dos'Santos et al., 2018; Jones et al., 2016a, 2016b; Jones et al., 2017), and CMAS (Jones et al., 2017) procedures were based on previously published methodologies (Dos'Santos et al., 2018; Jones et al., 2017), thus a brief overview is provided here.

Participants performed six trials of a 90° cut as fast as possible (70–90°) (Fig. 1). Completion time (2.11 ± 0.14 s, coefficient of variation = 2.71%) was measured to standardise performance between trials, and was assessed using two sets of Brower timing lights placed at hip height (Draper, UT, USA). Marker and force data were collected over the penultimate and final foot contact using ten Qualisys Oqus 7 (Gothenburg, Sweden) infrared cameras (240Hz) operating through Qualisys Track Manager software (Qualisys, version 2.16 (Build 3520), Gothenburg, Sweden) and GRF's were collected from two 600 mm × 900 mm AMTI (Advanced Mechanical Technology, Inc, Watertown, MA, USA) force platforms (Model number: 600900) embedded into the running track sampling at 1200Hz, respectively.

Using the pipeline function in visual 3D, joint coordinate (marker) and force data were smoothed using a Butterworth low-pass digital filter with cut-off frequencies of 15 and 25 Hz, based on *a priori* residual analysis (Winter 2009), visual inspection of motion data, and recommendations by Roewer et al. (Roewer, Ford, Myer, & Hewett, 2014). Lower limb joint moments were calculated using an inverse dynamics approach (Winter 1990) through Visual 3D software (C-motion, version 6.01.12, Germantown, USA) and were defined as external moments and normalised to body mass. Joint kinematics and GRF were also calculated using visual 3D, with Supplement 2 providing the variables examined, definitions, and calculations. Briefly, the following kinetic and kinematics were examined to provide insight into potentially "high-risk" cutting mechanics: vertical and horizontal GRF, knee flexion, rotation, and abduction angles and moments, hip rotation angle, trunk inclination angle, lateral foot plant distance, lateral trunk flexion, initial foot progression angle, and knee flexion angle. These aforementioned kinetic and kinematics were evaluated because they have been shown to be associated with greater multiplanar knee joint loads (Fox, 2018; Kristianslund et al., 2014; Weir et al., 2019), and have also been identified as visual characteristics of non-contact ACL injury during cutting (Johnston et al., 2018; Koga et al., 2010; Olsen et al., 2004). A more detailed rationale for investigation of these variables is presented in Supplement 1.

The trials were time normalised for each subject to 101 data points with each point representing 1% of the weight acceptance (WA) phase (0–100% of WA) of the cutting task. Initial contact was defined as the instant after ground contact that the vertical GRF was higher than 20 N, and end of contact was defined as the point where the vertical GRF subsided past 20 N (Jones et al., 2016b; Kristianslund et al., 2012, 2014). The WA phase was defined as the instant of initial contact to the point of maximum knee flexion (Havens & Sigward, 2015; Jones et al., 2015, 2016a). Approach velocities were $4.5 \pm 0.5\ \mathrm{m\,s^{-1}}$ at initial contact (touch-down) of the PFC, by calculating the horizontal centre off mass velocity using the combined lower-limb and trunk model, as recommended by Vanrenterghem et al. (Vanrenterghem, Gormley, Robinson, & Lees, 2010) and used previously in our laboratory (Jones et al., 2017).

Table 1
Cutting movement assessment score tool.

Camera	Variable	Observation	Score
Penultimate contact			
Side/ 45°	Clear PFC braking strategy (at initial contact) • Backward inclination of the trunk • Large COM to COP position – anterior placement of the foot • Effective deceleration – heel contact PFC	Y/N	Y = 0/N = 1
Final Contact			
Front/ 45°	**Wide lateral leg plant** (approx. > 0.35 m – dependent on subject anthropometrics) (at initial contact)	Y/N	Y = 2/N = 0
Front/ 45°	**Hip in an initial internally rotated position** (at initial contact)	Y/N	Y = 1/N = 0
Front/ 45°	**Initial knee 'valgus' position** (at initial contact)	Y/N	Y = 1/N = 0
All 3	**Foot not in neutral foot position** (at initial contact) Inwardly rotated foot position or externally rotated foot position (relative to original direction of travel)	Y/N	Y = 1/N = 0
Front/ 45°	**Frontal plane trunk position relative to intended direction; Lateral or trunk rotated towards stance limb, Upright, or Medial** (at initial contact and over WA)	L/TR/U/M	L/TR = 2/ U = 1, /M = 0
Side/ 45°	**Trunk upright or leaning back throughout contact** (not adequate trunk flexion displacement) (at initial contact and over WA)	Y/N	Y = 1/N = 0
Side/ 45°	**Limited Knee flexion during final contact (stiff) ≤ 30**° (over WA)	Y/N	Y = 1/N = 0
Front/ 45°	**Excessive Knee 'valgus' motion during contact** (over WA)	Y/N	Y = 1/N = 0

Key: PFC: Penultimate foot contact; COM: Centre of mass; COP: Centre of pressure; WA: weight acceptance; TR: Trunk rotation; Y: Yes; N: No; L: Lateral; TR: Trunk rotation; U: Upright; M: Medial.

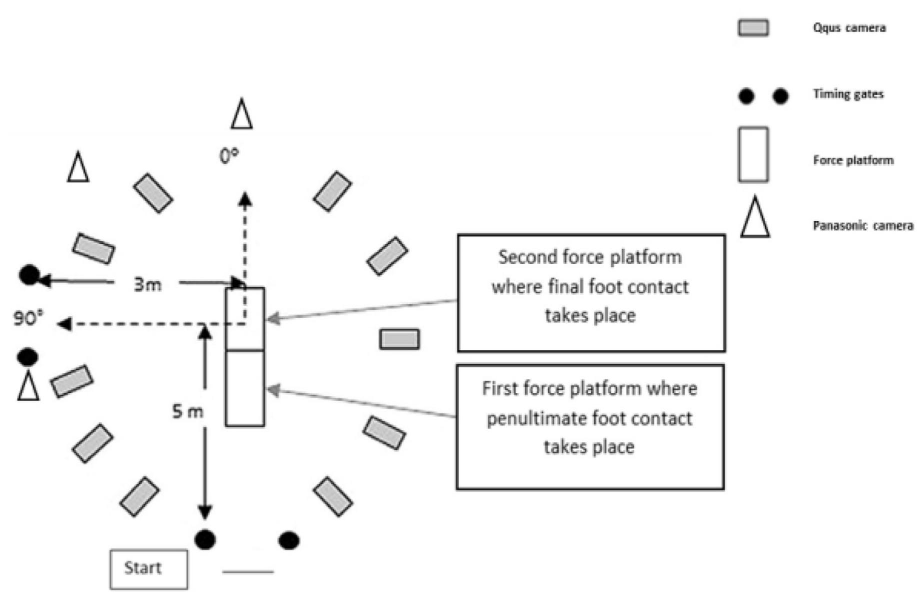

Fig. 1. Plan view of the experimental set-up. The task involved subjects approaching 5-m towards turning point on 2nd force platform. At the turning point, subjects cut to the left 90° using their right limb between timing gates placed 3-m away. Marker, GRF, and 2D camera data were collected simultaneously.

2.5. Qualitative assessment: CMAS

While marker and GRF data were collected, three Panasonic Lumix FZ-200 high speed cameras sampling at 100 Hz simultaneously filmed the cutting trials. These cameras were positioned on tripods 3-m away from the force plates at a height of 0.60 m and were placed in the sagittal and frontal plane, with a camera also placed 45° relative the cut, in accordance with previous recommendations (Jones et al., 2017) (Fig. 1). Video footage was subsequently viewed in Kinovea software (0.8.15 for Windows), which is free, and was used for qualitative screening using the CMAS (Table 1). This software allowed videos to be played at various speeds and frame-by-frame. The three raters were allowed to independently watch the videos as many times as necessary (Fort-Vanmeerhaeghe, Montalvo, Lloyd, Read, & Myer, 2017; Onate et al., 2010), at whatever speeds they needed to score each test, and could also pause footage for evaluative purposes (Fort-Vanmeerhaeghe et al., 2017). On average, qualitative screening of one trial took ~3 min.

Prior to qualitative screening, all raters attended a one-hour training session outlining how to grade the cutting trials using the CMAS, and to establish and uniformly agree on low-risk and high-risk movement patterns using pilot video footage. Subsequently, the lead researcher created a manual for all raters which contained guidelines, operational definitions (Supplement 1 and 3), and example images of low-risk and high-risk motions of each screening criteria to assist CMAS screening.

2.6. Statistical analyses

Thirty-two trials were discarded due to technical issues with camera footage, 3D data, or subjects slid or missed the platform that went unnoticed during data collection, thus resulting in 214 trials (minimum 4 trials from 41 athletes) screened and used for further analysis. All statistical analyses were performed in SPSS v 24 (SPSS Inc., Chicago, IL, USA) and Microsoft Excel (version 2016, Microsoft Corp., Redmond, WA, USA). To determine inter- and intra-rater reliability, 41 trials (one trial from each subject) were randomly selected by the lead researcher, similar to the procedures of previous research (Jones et al., 2017). The lead researcher, who has seven years' strength and conditioning and biomechanics experience, viewed and graded each trial on two separate occasions separated by 7 days, in line with previous research (Fort-Vanmeerhaeghe et al., 2017; Padua et al., 2009) to examine intra-rater reliability. Another researcher (experienced biomechanist; 17 years' biomechanics and strength and conditioning experience), viewed and graded each trial once and these scores were compared to the lead researcher to establish inter-rater reliability. In addition, a recent sports science graduate also viewed and graded each trial once and these scores were compared to the lead researcher to establish inter-rater reliability.

Intra-class correlation coefficients (ICC) (two-way mixed effects, average measures, absolute agreement) for total score were determined. Intraclass correlations were interpreted based on the following scale presented by Koo and Li (Koo & Li, 2016): poor (<0.50), moderate (0.50–0.75), good (0.75–0.90), and excellent (>0.90). For each item within the CMAS (Table 1), percentage agreements (agreements/agreements + disagreements × 100) and Kappa co-efficients were calculated. Kappa co-efficients were calculated using the formula; $k = \Pr(a) - \Pr(e)/1 - \Pr(e)$, where $\Pr(a)$ = relative observed agreement between raters; $\Pr(e)$ = hypothetic probability of chance agreement, which describes the proportion of agreement between the two methods after any agreement by chance has been removed (Viera & Garrett, 2005). The kappa co-efficient was interpreted based on the following scale of Landis and Koch (Landis & Koch, 1977): slight (0.01–0.20), fair (0.21–0.40), moderate (0.41–0.60), good (0.61–0.80), and excellent (0.81–1.00). Percentage agreements were interpreted in line with previous research (Cortes & Onate, 2013; Onate et al., 2010) and the scale was as follows: excellent (>80%), moderate (51–79%), and poor (<50%) (Cortes & Onate, 2013; Onate et al., 2010).

The relationship between CMAS and the "gold standard" determination of peak KAM during the final foot contact (FFC) of the cutting task from 3D motion analysis using the means of each subject was explored using Spearman's rank correlation, with 95% confidence intervals (CI), due to the non-parametric nature of the qualitative data. Correlations were evaluated as follows: trivial (0.00–0.09), 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 (1.00) (Hopkins, 2002). This analysis was performed using the 214 trials screened by the lead researcher.

Subjects were classified into low CMAS (bottom 33%, $n = 14$) and high CMAS (top 33%, $n = 14$) groups based on their mean CMASs. Subsequently, cutting 3D kinetics and kinematics were compared between the two groups (subject mean data) using independent sample t tests for parametric data and Mann-Whitney U tests for non-parametric data. To explore the magnitude of differences between groups, mean differences with 95% CIs and Hedges' *g* effect sizes with 95% CIs were also calculated as described previously (Hedges & Olkin, 1985), and interpreted as trivial (<0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), very large (2.0–3.99), and extremely large (≥4.00) (Hopkins, 2002). Statistical significance was defined $p \le 0.05$ for all tests.

3. Results

3.1. Intra- and inter-rater reliability

Excellent intra-rater reliability was observed for CMAS total score (ICC = 0.946). Intra- and inter-rater percentage agreements and Kappa coefficients are presented in Table 2. Excellent intra-rater percentage-agreements and kappa-coefficients were demonstrated for all CMAS variables (Table 2), with two variables scoring 100% agreement. For inter-rater reliability, most items displayed moderate to excellent percentage agreements (Table 2), while most items displayed moderate to good kappa coefficients between the lead researcher and experienced biomechanist. Conversely, kappa coefficients ranged from slight to good between the lead researcher and recent graduate, and most items displayed moderate to excellent percentage agreements (Table 2). Moderate inter-rater reliability was observed for CMAS total score between raters (ICC = 0.690).

3.2. Relationships between CMAS and peak KAM

Mean ± SD from each trial of the 41 subjects were 5.1 ± 1.8 CMAS and peak KAM 1.00 ± 0.44 Nm/kg. CMASs and KAMs for males and females were 5.1 ± 1.7, 1.07 ± 0.45 Nm/kg and 5.2 ± 2.1, KAM 0.81 ± 0.35 Nm/kg, respectively. Fig. 2 shows a linear and positive relationship between CMAS and peak KAMs. Spearman's correlation revealed a significant and very large ($\rho = 0.796$, 95% CI = 0.647–0.887, $p < 0.001$) association between CMAS and peak KAMs.

3.3. Comparisons in cutting 3D kinetics and kinematics between subjects with low and high CMASs

Descriptive statistics, *p* values, and effect sizes for kinetic and kinematic measures between subjects with low and high CMASs are presented in Table 3. Subjects with higher CMASs displayed significantly greater FFC mean VBFs, HBFs, and mean HBF ratios, and greater peak knee abduction angles, internal foot progression angles, and lateral foot plant distances (Table 3), with moderate to large effect sizes. Additionally, significantly greater cutting multi-planar knee joint loads (KFMs, KIRMs, and KAMs) were demonstrated by subjects with higher CMASs compared to lower (Table 3), with moderate to very large effect sizes.

4. Discussion

The primary aim of this study was to examine the validity and relationship between the CMAS attained from a qualitative screening tool and peak KAM quantified via 3D motion analysis. This study expanded on the preliminary work of Jones et al. (Jones et al., 2017) by using an additional camera filming at a higher sampling rate, and also investigating a larger sample size. In line with the study hypotheses, and substantiating Jones et al. (Jones et al., 2017), a very large ($\rho = 0.796$, $p < 0.001$) (Fig. 2) relationship was observed between CMAS and peak KAM. Moreover, "higher-risk" cutting mechanics associated with greater knee joint loading, thus ACL injury-risk, were displayed by subjects with higher CMASs (~7) compared to subjects with lower CMASs (~3) (Table 3). The CMAS also demonstrated excellent intra-rater reliability (Table 2), and generally moderate-to-excellent inter-rater reliability (Table 2). Therefore, these findings indicate that the CMAS qualitative screening tool can be considered a reliable and valid method to

Table 2
Intra- and inter-rater reliability for CMAS criteria and total score.

Variable/CMAS tool criteria	Intra-rater reliability (Lead researcher)		Inter-rater reliability - Lead research vs experienced biomechanist		Inter-rater reliability - Lead researcher vs recent graduate	
	% agreement	*k*	% agreement	*k*	% agreement	*k*
Clear PFC braking	97.6	0.940	82.9	0.633	82.9	0.633
Wide lateral leg plant	95.1	0.900	82.9	0.629	87.8	0.747
Hip in an initial internally rotated position	100.0	1.000	63.4	0.194	43.9	0.067
Initial knee 'valgus' position	90.2	0.805	75.6	0.512	75.6	0.512
Inwardly rotated foot position	100.0	1.000	80.5	0.599	90.2	0.784
Frontal plane trunk position relative to intended direction	90.2	0.805	73.2	0.551	87.8	0.767
Trunk upright or leaning back throughout contact	100.0	1.000	90.2	0.554	78.0	0.220
Limited Knee Flexion during final contact	97.6	0.932	80.5	0.431	80.5	0.381
Excessive Knee 'valgus' motion during contact	95.1	0.898	80.5	0.605	70.7	0.376
Average	96.2	0.920	78.9	0.52	77.5	0.50

Key: CMAS: Cutting movement assessment score; PFC: Penultimate foot contact.

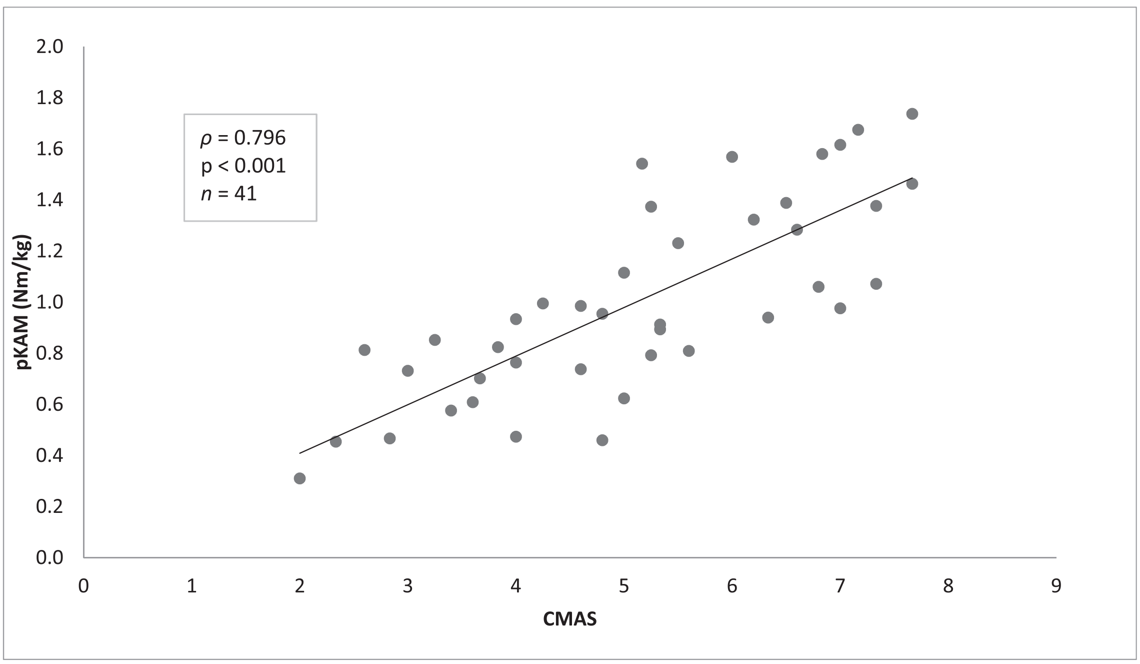

Fig. 2. Relationship between CMAS and peak KAMs (pKAM) subject mean data.

identify athletes who generate high KAMs and "high-risk" cutting mechanics. This tool offers practitioners a field-based screening method which can be included in testing and screening batteries for cutting sports so "high-risk" cutting deficits can be identified and "injury-risk profiles" can be created for athletes.

In light of kinetic and kinematics (high-risk) cutting deficits associated with greater knee joint loads during side-step cutting (Supplement 1), Jones et al. (Jones et al., 2017) developed the CMAS screening tool and reported a large relationship CMAS and peak KAM ($\rho = 0.633$; $p < 0.001$). Expanding on the preliminary investigation by Jones et al. (Jones et al., 2017), the present study observed a stronger relationship between CMAS and peak KAMs ($\rho = 0.796$, $p < 0.001$, Fig. 2), in a substantially greater sample size (41 vs. 8 subjects). The stronger relationships observed in the present study, compared to Jones et al. (Jones et al., 2017), could be attributed to the additional camera placed at 45° and increased sampling rate of the cameras (100 vs. 30 Hz). These additions may have permitted more accurate screening and evaluations of frontal and transverse plane deficits, such as trunk positioning and knee valgus. Nevertheless, these findings confirm that the CMAS is able to identify athletes who generate high peak KAMs, which offers practitioners a cheaper, time-efficient, and field-based applicable screening tool compared to 3D motion analysis using only three high-speed cameras and free video-analysis software.

While screening tools such as the LESS (Padua et al., 2009, 2011), TJA (Herrington et al., 2013b; Myer et al., 2008), and QASLS (Almangoush et al., 2014; Herrington et al., 2013) are useful for identifying abnormal and "high-risk" jump-landing mechanics, there is mixed evidence whether the examination of landing mechanics can identify athletes with poor cutting mechanics (Alenezi et al., 2014; Chinnasee et al., 2018; Kristianslund & Krosshaug, 2013; O'Connor et al., 2009). This issue is pertinent for practitioners who work with athletes who participate in cutting dominant sports. In addition, the LESS is the only screening tool to have been validated and assessed against 3D motion analysis (Onate et al., 2010; Padua et al., 2009), with no evidence to suggest that the TJA and QASLS is capable of identifying athletes who generate greater multiplanar knee joint loads. Conversely, in the present

Table 3
Comparisons in 3D cutting mechanics between subjects with lower and higher CMAS containing p values and effect size.

	Variable	Foot contact	Low CMAS ($n = 14$)		High CMAS ($n = 14$)		*p*	*g*	95% *g*		Mean difference	Mean difference 95% CI	
			Mean	*SD*	*Mean*	*SD*			LB	UB		LB	UB
	CMAS		3.34	0.70	6.95	0.63	**<0.001**	−5.29	−6.87	−3.72	−3.61	−4.13	−3.10
GRF	peak VBF (BW)	PFC	2.67	0.55	2.72	0.63	0.855	−0.07	−0.81	0.67	−0.04	−0.50	0.42
	mean VBF (BW)	PFC	0.95	0.16	0.97	0.20	0.879	−0.06	−0.80	0.68	−0.01	−0.15	0.13
	peak HBF/BW)	PFC	−1.53	0.52	−1.50	0.48	0.872	−0.06	−0.80	0.68	−0.03	−0.42	0.36
	mean HBF/BW)	PFC	−0.56	0.12	−0.53	0.14	0.617	−0.18	−0.92	0.56	−0.02	−0.12	0.07
	peak VBF (BW)	FFC	2.55	0.53	2.64	0.46	0.632	−0.18	−0.92	0.56	−0.09	−0.48	0.30
	mean VBF (BW)	FFC	1.54	0.18	1.71	0.21	**0.029**	−0.84	−1.61	−0.07	−0.17	−0.33	−0.02
	peak HBF (BW)	FFC	−1.44	0.35	−1.45	0.24	0.975	0.02	−0.73	0.76	0.00	−0.23	0.23
	mean HBF (BW)	FFC	−0.78	0.16	−0.94	0.13	**0.009**	1.03	0.24	1.82	0.16	0.04	0.27
	peak HBF ratio	both	1.03	0.35	1.06	0.39	*0.909*	−0.09	−0.83	0.66	−0.03	−0.32	0.26
	mean HBF ratio	both	1.42	0.29	1.88	0.65	***0.018***	−0.88	−1.66	−0.10	−0.45	−0.84	−0.06
Joint kinematics	peak KFA (°)	FFC	66.6	9.0	62.5	7.5	0.209	0.47	−0.28	1.22	4.0	−2.4	10.5
	KFA - IC (°)	FFC	23.1	5.1	23.6	4.9	0.766	−0.11	−0.85	0.63	−0.6	−4.5	3.3
	KFA ROM (°)	FFC	43.5	7.3	38.9	5.9	0.080	0.67	−0.09	1.43	4.6	−0.6	9.8
	peak KAA (°) (- abduction, + adduction)	FFC	−7.8	6.5	−13.4	6.6	**0.032**	0.83	0.06	1.60	5.6	0.5	10.7
	KAA - IC (°) (- abduction, + adduction)	FFC	4.3	4.8	0.6	4.7	0.052	0.75	−0.02	1.51	3.7	0.0	7.4
	KAA ROM (°)	FFC	−12.1	4.9	−14.0	5.4	0.321	0.37	−0.38	1.12	2.0	−2.0	5.9
	KRA - IC (°) (- internal, + external)	FFC	−10.7	6.9	−4.5	6.2	**0.020**	−0.91	−1.69	−0.13	−6.2	−11.3	−1.1
	peak KRA (°) (- internal, + external)	FFC	−9.6	7.4	−1.0	8.6	**0.009**	−1.04	−1.83	−0.25	−8.6	−14.8	−2.3
	Hip rotation angle - IC (°) (- internal, + external)	FFC	11.0	7.1	7.9	10.6	0.377	0.33	−0.42	1.08	3.1	−3.9	10.1
Technique	Trunk inclination angle - IC (°) (relative to vertical line, + forward, - backward)	PFC	6.8	3.9	8.1	3.4	0.361	−0.34	−1.09	0.41	−1.3	−4.1	1.6
	Trunk inclination angle - IC (°) (relative to vertical line, + forward, - backward)	FFC	17.2	31.3	10.4	6.0	0.437	0.29	−0.46	1.03	6.7	−10.8	24.2
	IFPA - IC (°) (- internal, + external)	FFC	9.0	10.2	25.5	9.3	**<0.001**	−1.64	−2.49	−0.78	−16.5	−24.1	−8.9
	Lateral trunk flexion - IC (°) (- over stance leg, + direction of travel)	FFC	−18.4	8.0	−17.6	7.3	0.794	−0.10	−0.84	0.64	−0.8	−6.7	5.2
	Lateral foot plant distance - IC (m)	FFC	−0.299	0.041	−0.336	0.044	**0.028**	0.85	0.08	1.63	0.038	0.004	0.071
Joint moment	peak KFM (Nm/kg)	FFC	3.06	0.60	3.64	0.72	**0.027**	−0.86	−1.64	−0.09	−0.59	−1.10	−0.07
	peak KRM (Nm/kg) (- internal, + external)	FFC	−0.69	0.39	−1.10	0.61	**0.047**	0.77	0.01	1.54	0.41	0.01	0.81
	peak KAM (Nm/kg) (+abduction, - adduction)	FFC	0.73	0.27	1.37	0.28	**<0.001**	2.24	−3.18	−1.29	−0.63	−0.85	−0.42

Key: VBF: Vertical braking force; HBF: Horizontal braking force; FFC: Final foot contact; PFC: Penultimate foot contact; IC: Initial contact; BW: Body weight; KFA: Knee flexion angle; ROM: Range of motion; KAA: Knee abduction angle; KRA: Knee rotation angle; IFPA: Initial foot progression angle; KFM: Knee flexor moment; KRM: Knee rotation moment; KAM: Knee abduction moment; ES: Effect size; CMAS: Cutting movement assessment scores; Sag: Sagittal. CI: Confidence interval; LB: Lower bound; UB: Upper bounds; ES: Effect size. Note: Bold denotes statistically significant difference ($p < 0.05$) and italic denotes non-parametric.

study, "higher-risk" cutting mechanics and greater multiplanar knee joint loads (Table 3) were demonstrated by subjects with high CMASs compared to subjects with low CMASs. These "higher-risk" mechanics included greater mean VBF and HBFs, greater KAAs, greater lateral foot plant distances, greater internal foot progression angles, and lower knee flexion ROM (Table 3), with moderate to large effect sizes. Moreover, greater multiplanar knee joint loads (knee flexion, abduction, and internal rotation moments) were also demonstrated by subjects with high CMASs compared to low, with moderate to very large effect sizes (Table 3). This finding is important because combined multiplanar loads strain the ACL to a greater extent compared to uniplanar loading (Bates et al., 2015; Markolf et al., 1995; Shin et al., 2011). Krosshaug et al. (Krosshaug et al., 2007a) has highlighted the potential difficulties in estimating 3D joint kinematics based on 2D video evaluations of cutting mechanics. Conversely, the results indicate that the raters in the present study were capable of accurately evaluating and identifying aberrant lower-limb and trunk postures during cutting, as confirmed by the measurable difference in 3D kinetics and kinematics between subjects with "high" and "low" CMASs related to the CMAS scoring system (Table 3).

Supporting Jones et al. (Jones et al., 2017), higher CMASs were associated with greater peak KAMs (Fig. 2), and "higher-risk" cutting mechanics were displayed by subjects with high CMASs (Table 3). These findings indicate that higher scores are representative of, in general, poorer cutting technique. The CMAS tool can therefore be useful for practitioners who want to screen and evaluate cutting movement quality to identify potentially "high-risk" athletes (Herrington et al., 2018; Hewett, 2016; McCunn & Meyer, 2016; Mok & Leow, 2016), so these athletes can be targeted with biomechanical and neuromuscular informed training interventions to reduce potential injury-risk (Herrington et al., 2018; Hewett, 2016; Mok & Leow, 2016). Qualitative screening tools such as the JTA (Klugman, Brent, Myer, Ford, & Hewett, 2011), LESS (Distefano et al., 2016; Parsons, Sylvester, & Porter, 2017), and QASLS (Dawson & Herrington, 2015) have been used to monitor the effectiveness of training interventions on jump-landing or single leg control mechanics; therefore, the CMAS could be used to monitor pre-to-post changes in cutting movement quality in response to training interventions, and is subsequently a recommended future direction of research. However, it is emphasised that lower CMASs do not necessarily equate to optimal or "safe" technique, and practitioners should not only focus on total score, but focus on the CMAS criteria where athletes scored deficits (Fox et al., 2015; Jones et al., 2017). For example, an athlete who scores 2–3 points may still display "high-risk" cutting deficits such as knee valgus, lateral trunk flexion, limited knee flexion, or hip internal rotation and thus, would still warrant specific injury-risk mitigation training and conditioning. As such, practitioners should be cautious and are advised to look beyond the total CMAS score and use the CMAS tool to assist in the identification of potentially "high-risk" cutting deficits. The information attained from the CMAS may help inform the future prescription of training and conditioning to correct these deficits, and thus potential injury risk (Herrington et al., 2018; Hewett, 2016; Mok & Leow, 2016).

Although a plethora of investigations have focused on COD biomechanics associated with increased risk of injury and have identified a range of factors linked to knee joint loading (Table 1) (Dempsey et al., 2007; Frank et al., 2013; Havens & Sigward, 2015; Jamison et al., 2012; Jones et al., 2015, 2016a; Kristianslund et al., 2014; McLean et al., 2005; Sigward et al., 2015; Sigward & Powers, 2007; Weir et al., 2019), technical guidelines for coaching safer side-step cutting are limited. A unique aspect of the CMAS is that the criteria (Table 1) can be used as a technical framework for coaching safer side-step cutting which practitioners can use when working with their athletes (Jones et al., 2017). COD technique modification has been shown to be an effective modality for reducing high-risk mechanics and knee joint loading during COD (Dai et al., 2014; Dempsey, Lloyd, Elliott, Steele, & Munro, 2009). Consequently, using the CMAS as a screening tool and a technical framework for safer cutting could be a viable strategy which coaches and practitioners could use to identify specific "high-risk" cutting deficits (i.e. lateral trunk flexion, knee valgus) to help inform preventative COD technique modification training.

It is worth noting, however, that some of the "high-risk" cutting deficits may be needed for faster cutting performance (Dai et al., 2014; Fox, 2018; Havens & Sigward, 2015). For example, a wide lateral foot plant is needed to generate medio-lateral propulsive force and impulse (Havens & Sigward, 2015; Jones et al., 2015), thus subsequent exit velocity; however, this technique concurrently elevates peak KAMs (Dempsey et al., 2007; Jones et al., 2015; Kristianslund et al., 2014). Limited knee flexion and motion is associated with potentially shorter GCTs (Dai et al., 2014; Fox, 2018), but this posture increases KAMs (Kristianslund et al., 2014; Weir et al., 2019), knee flexor joint loads and GRFs (Dai et al., 2014; Zhang, Bates, & Dufek, 2000), thus potential injury-risk (Fox, 2018). Moreover, lateral trunk flexion, from an attacking and evasive perspective, may be performed to feint and deceive opponents (Brault, Bideau, Kulpa, & Craig, 2012), but is a critical factor that augments potentially hazardous KAMs (Dempsey et al., 2007; Hewett et al., 2009). Consequently, practitioners should acknowledge the trade-off between knee joint loading (injury-risk) and performance when screening cutting mechanics, because some of the high-risk deficits demonstrated could be effective for performance. Nonetheless, practitioners should ensure that their athletes' have the physical capacity (i.e. neuromuscular control, co-contraction, and rapid force production) to tolerate the knee joint loading demands of side-steps (Jones et al., 2015; Lloyd & Buchanan, 2001; Padua et al., 2018). Further research is required to improve our understanding of the potential performance-injury conflict during cutting (Fox, 2018).

5. Limitations

It should be acknowledged that, due to the multiplanar nature of side-step cutting (Besier et al., 2001b), some athletes pre-rotate towards the direction of travel during weight acceptance of the cut (Sigward et al., 2015). This pre-rotation can potentially result in parallax error because the athlete is not perpendicular to the cameras which can restrict evaluations of particular CMAS criteria using the frontal plane and 45° cameras. Additionally, the current study only investigated a side-step cutting action; thus, the CMAS screening tool is specific to side-step cutting only. Specific screening tools must be developed and validated for assessing other COD actions, such as crossover cuts and pivots, which are also performed and associated with injury in multidirectional sport (Cochrane, Lloyd, Buttfield, Seward, & McGivern, 2007; Johnston et al., 2018). However, side-step cutting appears to be the predominant COD action associated with non-contact ACL injury (Cochrane et al., 2007); therefore, highlighting the importance and inclusion of side-step cutting screening tools (CMAS) in testing batteries for athletes who participate in cutting sports, such as soccer, rugby, handball, American football, and badminton. Furthermore, the intra- and inter-rater reliability, generally, was moderate to excellent (Table 2), but limited to biomechanists and strength and conditioning coaches. Further work is required to establish agreements and reliability between different applied practitioners, such as sports rehabilitators, physiotherapists, and sports coaches, in order to confirm its efficacy in the field. Finally, a pre-planned cutting task was used in the present study; however, results of previous research have shown that unplanned side-stepping results in greater knee joint loads, more abnormal mechanics, and less muscle support to counteract the greater loads compared to pre-planned side-stepping (Besier, Lloyd, Ackland, & Cochrane, 2001, 2003; Brown, Brughelli, & Hume, 2014).

6. Conclusion

In conclusion, a very large significant relationship was observed between CMAS and peak KAM, and "higher-risk" cutting mechanics associated with greater knee joint loading were displayed by subjects with "high" CMASs (~7) compared to subjects with "low" CMASs (~3). As such, the CMAS is a valid and reliable screening tool for evaluating side-step cutting movement quality and offers practitioners a cost-effective and easily applicable field-based screening tool to identify athletes who generate high peak KAMs during side-step cutting. Practitioners should therefore consider including the CMAS in their fitness and testing batteries when screening and profiling athletes who participate in multidirectional sports. Equally, the CMAS allows practitioners to identify "high-risk" cutting deficits in athletes and subsequently create an "injury-risk profile". These identified deficits can be targeted and addressed through biomechanical and neuromuscular informed training interventions. Finally, the CMAS can be used as a potential technical framework for coaching "safer" cutting.

Ethical statement

Ethical Approval for the study was provided by the Ethics committee at the University of Salford (HSR1617-02). The work described has been carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki). All subjects provided written informed consent prior to participating in the study.

Declarations of interest

None declared.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgements

The authors would like to thank all participants for partaking in this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2019.05.004.

References

Alenezi, F., Herrington, L., Jones, P., & Jones, R. (2014). Relationships between lower limb biomechanics during single leg squat with running and cutting tasks: A preliminary investigation. *British Journal of Sports Medicine, 48*, 560–561.

Almangoush, A., Herrington, L., & Jones, R. (2014). A preliminary reliability study of a qualitative scoring system of limb alignment during single leg squat. *Physical Therapy and Rehabilitation, 1*(2).

Bahr, R. (2016). Why screening tests to predict injury do not work and probably never will: A critical review. *British Journal of Sports Medicine, 50*, 776–780.

Bates, N. A., Myer, G. D., Shearn, J. T., & Hewett, T. E. (2015). Anterior cruciate ligament biomechanics during robotic and mechanical simulations of physiologic and clinical motion tasks: A systematic review and meta-analysis. *Clinical Biomechanics, 30*, 1–13.

Besier, T. F., Lloyd, D. G., & Ackland, T. R. (2003). Muscle activation strategies at the knee during running and cutting maneuvers. *Medicine & Science in Sports & Exercise, 35*, 119–127.

Besier, T. F., Lloyd, D. G., Ackland, T. R., & Cochrane, J. L. (2001). Anticipatory effects on knee joint loading during running and cutting maneuvers. *Medicine & Science in Sports & Exercise, 33*, 1176–1181.

Besier, T. F., Lloyd, D. G., Cochrane, J. L., & Ackland, T. R. (2001). External loading of the knee joint during running and cutting maneuvers. *Medicine & Science in Sports & Exercise, 33*, 1168–1175.

Bittencourt, N. F. N., Meeuwisse, W. H., MendonÃ§a, L. D., Nettel-Aguirre, A., Ocarino, J. M., & Fonseca, S. T. (2016). Complex systems approach for sports injuries: Moving from risk factor identification to injury pattern recognition-narrative review and new concept. *British Journal of Sports Medicine, 50*, 1309–1314.

Boden, B. P., Dean, G. S., Feagin, J. A., & Garrett, W. E. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics, 23*, 573–578.

Brault, S., Bideau, B., Kulpa, R., & Craig, C. M. (2012). Detecting deception in movement: The case of the side-step in rugby. *PLoS One, 7*, e37494.

Brown, S. R., Brughelli, M., & Hume, P. A. (2014). Knee mechanics during planned and unplanned sidestepping: A systematic review and meta-analysis. *Sports Medicine, 44*, 1573–1588.

Camomilla, V., Cereatti, A., Cutti, A. G., Fantozzi, S., Stagni, R., & Vannozzi, G. (2017). Methodological factors affecting joint moments estimation in clinical gait analysis: A systematic review. *BioMedical Engineering Online, 16*, 106.

Chinnasee, C., Weir, G., Sasimontonkul, S., Alderson, J., & Donnelly, C. (2018). A biomechanical comparison of single-leg landing and unplanned sidestepping. *Int J Sports Med, 39*, 636–645.

Cochrane, J. L., Lloyd, D. G., Buttfield, A., Seward, H., & McGivern, J. (2007). Characteristics of anterior cruciate ligament injuries in Australian football. *Journal of Science and Medicine in Sport, 10*, 96–104.

Cortes, N., & Onate, J. (2013). Clinical assessment of drop-jump landing for determination of risk for knee injury. *International Journal of Athletic Therapy & Training, 18*, 10–13.

Dai, B., William, E. G., Michael, T. G., Darin, A. P., Robin, M. Q., & Bing, Y. (2014). The effects of 2 landing techniques on knee kinematics, kinetics, and performance during stop-jump and side-cutting tasks. *The American Journal of Sports Medicine, 43*, 466–474.

Dawson, S. J., & Herrington, L. (2015). Improving single-Leggedâ€"Squat performance: Comparing 2 training methods with potential implications for injury prevention. *Journal of Athletic Training, 50*, 921–929.

Dempsey, A. R., Lloyd, D. G., Elliott, B. C., Steele, J. R., & Munro, B. J. (2009). Changing sidestep cutting technique reduces knee valgus loading. *The American Journal of Sports Medicine, 37*, 2194–2200.

Dempsey, A. R., Lloyd, D. G., Elliott, B. C., Steele, J. R., Munro, B. J., & Russo, K. A. (2007). The effect of technique change on knee loads during sidestep cutting. *Medicine & Science in Sports & Exercise, 39*, 1765–1773.

Distefano, L. J., Marshall, S. W., Padua, D. A., Peck, K. Y., Beutler, A. I., de la Motte, S. J., et al. (2016). The effects of an injury prevention program on landing biomechanics over time. *The American Journal of Sports Medicine, 44*, 767–776.

Dos'Santos, T., Comfort, P., & Jones, P. A. (2018). Average of trial peaks versus peak of average profile: Impact on change of direction biomechanics. *Sports Biomechanics, 1–10*.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G* Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods, 41*, 1149–1160.

Fort-Vanmeerhaeghe, A., Montalvo, A. M., Lloyd, R. S., Read, P., & Myer, G. D. (2017). Intra-and inter-rater reliability of the modified tuck jump assessment. *Journal of Sports Science and Medicine, 16*, 117.

Fox, A. (2018). Change-of-Direction biomechanics: Is What's best for anterior cruciate ligament injury prevention also best for performance? *Sports Medicine, 48*, 1799–1807.

Fox, A. S., Bonacci, J., McLean, S. G., & Saunders, N. (2017). Efficacy of ACL injury risk screening methods in identifying high-risk landing patterns during a sport-specific task. *Scandinavian Journal of Medicine & Science in Sports, 27*, 525–534.

Fox, A. S., Bonacci, J., McLean, S. G., Spittle, M., & Saunders, N. (2016). A systematic evaluation of field-based screening methods for the assessment of anterior cruciate ligament (ACL) injury risk. *Sports Medicine, 46*, 715–735.

Fox, A., Spittle, M., Otago, L., & Saunders, N. (2014). Offensive agility techniques performed during international netball competition. *International Journal of Sports Science & Coaching, 9*, 543–552.

Frank, B., Bell, D. R., Norcross, M. F., Blackburn, J. T., Goerger, B. M., & Padua, D. A. (2013). Trunk and hip biomechanics influence anterior cruciate loading mechanisms in physically active participants. *The American Journal of Sports Medicine, 41*, 2676–2683.

Havens, K., & Sigward, S. M. (2015). Cutting mechanics: Relation to performance and anterior cruciate ligament injury risk. *Medicine & Science in Sports & Exercise, 47*, 818–824.

Hedges, L., & Olkin, I. (1985). *Statistical methods for meta-analysis*. New York: Acdemic Press.

Herrington, L. C., Munro, A. G., & Jones, P. A. (2018). Assessment of factors associated with injury risk. *Performance Assessment in Strength and Conditioning, 53–95*.

Herrington, L., Myer, G., & Horsley, I. (2013). Task based rehabilitation protocol for elite athletes following anterior cruciate ligament reconstruction: A clinical commentary. *Physical Therapy in Sport, 14*, 188–198.

Herrington, L., Myer, G. D., & Munro, A. (2013). Intra and inter-tester reliability of the tuck jump assessment. *Physical Therapy in Sport, 14*, 152–155.

Hewett, T. E. (2016). Response to:"Why screening tests to predict injury do not work -and probably never will...: A critical review. *British Journal of Sports Medicine, 50*, 1353-1353.

Hewett, T. (2017). Preventive biomechanics: A paradigm shift with a translational approach to biomechanics. *The American Journal of Sports Medicine, 45*, 2654–2664.

Hewett, T. E., Torg, J. S., & Boden, B. P. (2009). Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: Lateral trunk and knee abduction motion are combined components of the injury mechanism. *British Journal of Sports Medicine, 43*, 417–422.

Hopkins, W. G. (2002). *A scale of magnitudes for effect statistics. A new view of statistics*. Retrieved from http://sportsci.org/resource/stats/effectmag.html.

Jamison, S. T., Pan, X., & Chaudhari, A. M. W. (2012). Knee moments during run-to-cut maneuvers are associated with lateral trunk positioning. *Journal of Biomechanics, 45*, 1881–1885.

Johnston, J. T., Mandelbaum, B. R., Schub, D., Rodeo, S. A., Matava, M. J., Silvers, H. J., et al. (2018). Video analysis of anterior cruciate ligament tears in professional American football athletes. *The American Journal of Sports Medicine, 46*, 862–868.

Jones, P. A., Donelon, T., & Dos' Santos, T. (2017). *A preliminary investigation into a qualitative assessment tool to identify athletes with high knee abduction moments during cutting: Cutting Movement Assessment Score (CMAS)*. Professional Strength and Conditioning.

Jones, P., Herrington, L., & Graham-Smith, P. (2015). Technique determinants of knee joint loads during cutting in female soccer players. *Human Movement Science, 42*, 203–211.

Jones, P., Herrington, L., & Graham-Smith, P. (2016a). Braking characteristics during cutting and pivoting in female soccer players. *Journal of Electromyography and Kinesiology, 30*, 46–54.

Jones, P., Herrington, L., & Graham-Smith, P. (2016b). Technique determinants of knee abduction moments during pivoting in female soccer players. *Clinical Biomechanics, 31*, 107–112.

Jones, P. A., Herrington, L. C., Munro, A. G., & Graham-Smith, P. (2014). Is there a relationship between landing, cutting, and pivoting tasks in terms of the characteristics of dynamic valgus? *The American Journal of Sports Medicine, 42*, 2095–2102.

Jones, P., Thomas, C., Dos'Santos, T., McMahon, J., & Graham-Smith, P. (2017). The role of eccentric strength in 180° turns in female soccer players. *Sports, 5*(42).

Kimura, Y., Ishibashi, Y., Tsuda, E., Yamamoto, Y., Tsukada, H., & Toh, S. (2010). Mechanisms for anterior cruciate ligament injuries in badminton. *British Journal of Sports Medicine, 44*, 1124–1127.

Klugman, M. F., Brent, J. L., Myer, G. D., Ford, K. R., & Hewett, T. E. (2011). Does an in-season only neuromuscular training protocol reduce deficits quantified by the tuck jump assessment? *Clinics in Sports Medicine, 30*, 825–840.

Koga, H., Nakamae, A., Shima, Y., Iwasa, J., Myklebust, G., Engebretsen, L., et al. (2010). Mechanisms for noncontact anterior cruciate ligament injuries knee joint kinematics in 10 injury situations from female team handball and basketball. *The American Journal of Sports Medicine, 38*, 2218–2225.

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine, 15*, 155–163.

Kristianslund, E., Faul, O., Bahr, R., Myklebust, G., & Krosshaug, T. (2014). Sidestep cutting technique and knee abduction loading: Implications for ACL prevention exercises. *British Journal of Sports Medicine, 48*, 779–783.

Kristianslund, E., & Krosshaug, T. (2013). Comparison of drop jumps and sport-specific sidestep cutting: Implications for anterior cruciate ligament injury risk screening. *The American Journal of Sports Medicine, 41*, 684–688.

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. *Journal of Biomechanics, 45*, 666–671.

Krosshaug, T., Nakamae, A., Boden, B., Engebretsen, L., Smith, G., Slauterbeck, J., et al. (2007). Estimating 3D joint kinematics from video sequences of running and cutting maneuvers—assessing the accuracy of simple visual inspection. *Gait & Posture, 26*, 378–385.

Krosshaug, T., Nakamae, A., Boden, B. P., Engebretsen, L., Smith, G., Slauterbeck, J. R., et al. (2007). Mechanisms of anterior cruciate ligament injury in basketball video analysis of 39 cases. *The American Journal of Sports Medicine, 35*, 359–367.

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, 159–174.

Lloyd, D. G., & Buchanan, T. S. (2001). Strategies of muscular support of varus and valgus isometric loads at the human knee. *Journal of Biomechanics, 34*, 1257–1267.

Markolf, K. L., Burchfield, D. M., Shapiro, M. M., Shepard, M. F., Finerman, G. A. M., & Slauterbeck, J. L. (1995). Combined knee loading states that generate high anterior cruciate ligament forces. *Journal of Orthopaedic Research, 13*, 930–935.

McCunn, R., & Meyer, T. (2016). Screening for risk factors: If you liked it then you should have put a number on it. *British Journal of Sports Medicine, 50*, 1354.

McLean, S. G., Huang, X., & van den Bogert, A. J. (2005). Association between lower extremity posture at contact and peak knee valgus moment during side-stepping: Implications for ACL injury. *Clinical Biomechanics, 20*, 863–870.

McLean, S. G., Walker, K., Ford, K. R., Myer, G. D., Hewett, T. E., & van den Bogert, A. J. (2005). Evaluation of a two dimensional analysis method as a screening and evaluation tool for anterior cruciate ligament injury. *British Journal of Sports Medicine, 39*, 355–362.

Mok, K.-M., & Leow, R.-S. (2016). Measurement of movement patterns to enhance ACL injury prevention-A dead end? *Journal of Sports Medicine Arthroscopy, Rehabilitation, Technology, 5*, 13–16.

Montgomery, C., Blackburn, J., Withers, D., Tierney, G., Moran, C., & Simms, C. (2018). Mechanisms of ACL injury in professional rugby union: A systematic video analysis of 36 cases. *British Journal of Sports Medicine, 52*, 944–1001.

Munro, A. G., Herrington, L., & Comfort, P. (2017). The relationship between 2-dimensional knee-valgus angles during single-leg squat, single-leg-land, and drop-jump screening tests. *Journal of Sports Rehabilitation, 26*, 72–77..

Myer, G. D., Brent, J. L., Ford, K. R., & Hewett, T. E. (2011). Real-time assessment and neuromuscular training feedback techniques to prevent ACL injury in female athletes. *Strength and Conditioning Journal, 33*, 21–35.

Myer, G. D., Ford, K. R., & Hewett, T. E. (2008). Tuck jump assessment for reducing anterior cruciate ligament injury risk. *Athletic Therapy Today: The Journal for Sports Health Care Professionals, 13*(39), 39–44.

O'Connor, K. M., Monteiro, S. K., & Hoelker, I. A. (2009). Comparison of selected lateral cutting activities used to assess ACL injury risk. *Journal of Applied Biomechanics, 25*, 9–21.

Olsen, O.-E., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury mechanisms for anterior cruciate ligament injuries in team handball a systematic video analysis. *The American Journal of Sports Medicine, 32*, 1002–1012.

Onate, J., Cortes, N., Welch, C., & Van Lunen, B. (2010). Expert versus novice inter-rater reliability and criterion validity of the landing error scoring system. *Journal of Sport Rehabilitation, 19*, 41–56.

Padua, D. A., Boling, M. C., DiStefano, L. J., Onate, J. A., Beutler, A. I., & Marshall, S. W. (2011). Reliability of the landing error scoring system-real time, a clinical assessment tool of jump-landing biomechanics. *Journal of Sport Rehabilitation, 20*, 145–156.

Padua, D. A., DiStefano, L. J., Hewett, T. E., Garrett, W. E., Marshall, S. W., Golden, G. M., et al. (2018). National athletic trainers' association position statement: Prevention of anterior cruciate ligament injury. *Journal of Athletic Training, 53*, 5–19.

Padua, D. A., Marshall, S. W., Boling, M. C., Thigpen, C. A., Garrett, W. E., & Beutler, A. I. (2009). The landing error scoring system (LESS) is a valid and reliable clinical assessment tool of jump-landing biomechanics the JUMP-ACL study. *The American Journal of Sports Medicine, 37*, 1996–2002.

Parsons, J. L., Sylvester, R., & Porter, M. M. (2017). The effect of strength training on the jump-landing biomechanics of young female athletes: Results of a randomized controlled trial. *Clinical Journal of Sport Medicine, 27*, 127–132.

Quatman, C. E., Quatman-Yates, C. C., & Hewett, T. E. (2010). A 'Plane'Explanation of anterior cruciate ligament injury mechanisms. *Sports Medicine, 40*, 729–746.

Roewer, B. D., Ford, K. R., Myer, G. D., & Hewett, T. E. (2014). The 'impact' of force filtering cut-off frequency on the peak knee abduction moment during landing: Artefact or 'artifiction'? *British Journal of Sports Medicine, 48*, 464–468.

Shin, C. S., Chaudhari, A. M., & Andriacchi, T. P. (2011). Valgus plus internal rotation moments increase anterior cruciate ligament strain more than either alone. *Medicine & Science in Sports & Exercise, 43*, 1484–1491.

Sigward, S. M., Cesar, G. M., & Havens, K. L. (2015). Predictors of frontal plane knee moments during side-step cutting to 45 and 110 degrees in men and women: Implications for anterior cruciate ligament injury. *Clinical Journal of Sport Medicine, 25*, 529–534.

Sigward, S. M., & Powers, C. M. (2007). Loading characteristics of females exhibiting excessive valgus moments during cutting. *Clinical Biomechanics, 22*, 827–833.

Stuelcken, M. C., Mellifont, D. B., Gorman, A. D., & Sayers, M. G. (2016). Mechanisms of anterior cruciate ligament injuries in elite women's netball: A systematic video analysis. *Journal of Sports Science, 34*, 1516–1522.

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*, 517–521.

Viera, A. J., & Garrett, J. M. (2005). Understanding interobserver agreement: The kappa statistic. *Family Medicine, 37*, 360–363.

Walden, M., Krosshaug, T., Bjorneboe, J., Andersen, T. E., Faul, O., & Hagglund, M. (2015). Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: A systematic video analysis of 39 cases. *British Journal of Sports Medicine, 49*, 1452–1460.

Weir, G., Alderson, J., Smailes, N., Elliott, B., & Donnelly, C. (2019). A reliable video-based ACL injury screening tool for female team sport athletes. *International Journal of Sports Medicine, 40*, 191–199.

Wheeler, K. W., Askew, C. D., & Sayers, M. G. (2010). Effective attacking strategies in rugby union. *European Journal of Sport Science, 10*, 237–242.

Winter, D. A. (1990). *Biomechanics and motor control of human motion*. New York: Wiley-Interscience.

Winter, D. A. (2009). *Biomechanics and motor control of human movement*. John Wiley & Sons.

Zhang, S.-N., Bates, B. T., & Dufek, J. S. (2000). Contributions of lower extremity joints to energy dissipation during landings. *Medicine & Science in Sports & Exercise, 32*, 812–819.