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Journal of Biomechanics 191 (2025) 112896

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech

Knee abduction moment waveforms and effect sizes during sidestepping interventions: A critical perspective to inform adequately powered future studies

Hazel Tucker [a,d], Jos Vanrenterghem [b,1], Todd C. Pataky [c,2], Mark A. Robinson [a,*]

[a] School of Sport and Exercise Sciences, Liverpool John Moores University, UK
[b] Musculoskeletal Rehabilitation Research Group, Faculty of Movement and Rehabilitation Sciences, KU Leuven, Belgium
[c] Department of Human Health Sciences, Kyoto University, Japan
[d] Cardiff School of Sport and Health Sciences, Cardiff Metropolitan University, Cardiff, UK

ARTICLE INFO

Keywords:
ACL
Statistical power
Sample size
Primary outcome measure
Injury risk

ABSTRACT

The knee abduction moment (KAM) is often chosen as target of intervention studies to reduce anterior cruciate ligament injury risk. Outcome variables such as the KAM should be reproducible and responsive to change. This study critically evaluated the suitability of the KAM as an outcome variable for sidestepping interventions. Firstly, peak KAM effect sizes from either a within-day technique manipulation or long-term intervention studies were extracted using a systematic literature search. Effect sizes varied substantially from small to large effects. Secondly, power reporting practice across intervention studies was evaluated and was found to be generally not reproducible. Thirdly, KAM profiles were digitised to establish the consistency of reported KAM signals and to establish a representative KAM profile. Lastly, median KAM effect sizes from a within-day technique manipulation and long-term interventions were separately combined with the representative KAM profile for a hypothetical KAM reduction input to a waveform-level sample size estimation analysis. Sample sizes to observe a reduction of the median KAM effect size were ~255 for a within-day technique manipulation and ~360 long-term interventions. Intervention studies tended to observe smaller effect sizes than were calculated in their power analysis. Sample sizes needed to power hypothetical KAM reduction studies with median effect sizes were somewhat prohibitive. These results support the accumulating evidence that the KAM is not a suitable primary outcome measure against which intervention studies should be designed and evaluated.

1. Introduction

Anterior cruciate ligament (ACL) injury is a serious and debilitating injury (Faude et al., 2005; Joseph et al., 2013; Olsen et al., 2004). The short-term impact on the sufferer is significant and there is an increased risk of developing osteoarthritis later in life (Lohmander et al., 2007). ACL injuries happen in a range of sports, however there are some common movements such as decelerating, landing and changing direction during which they often occur (Faude et al., 2005; Olsen et al., 2004; Walden et al., 2015). Although a range of biomechanical risk factors have been identified (Hughes, 2014), one that has received considerable attention is the knee abduction moment (KAM). The relationship between the KAM and ACL strain *in-vitro* is well established; an increased KAM increases ACL strain (Markolf et al., 1995; Shin et al., 2009; Withrow et al., 2006). *In-vivo*, however, the evidence linking KAM to ACL injury occurrence is less compelling with one prospective study finding that higher KAM during drop jumping indicated athletes at higher risk of ACL injury (Hewett et al., 2005). Subsequent studies in similar and other tasks have not corroborated this (Cronstrom et al., 2020; Krosshaug et al., 2016; Leppänen et al., 2017). Nevertheless, the sidestepping task is generally agreed to provide a sufficient single-leg challenge as it replicates injury situations and so is often chosen to evaluate injury risk interventions.

There is little doubt that the KAM has emerged as a primary

* Corresponding author.
E-mail addresses: st20188133@outlook.cardiffmet.ac.uk (H. Tucker), jos.vanrenterghem@kuleuven.be (J. Vanrenterghem), pataky.todd.2m@kyoto-u.ac.jp (T.C. Pataky), m.a.robinson@ljmu.ac.uk (M.A. Robinson).
[1] ORCID ID: 0000-0002-1682-8430.
[2] ORCID ID: 0000-0002-8292-7189.

https://doi.org/10.1016/j.jbiomech.2025.112896
Accepted 7 August 2025
Available online 8 August 2025

biomechanical determinant of ACL injury risk as evidenced in several recent reviews (Donelon et al., 2020; Dos Santos et al., 2019; Fox, 2018; Lima et al., 2024; Weir, 2022). It is often chosen as a key metric that interventions, technique modifications, and injury prevention programmes are evaluated against. But there has been little consideration if the KAM is indeed a suitable primary outcome variable. The poor reporting of suitable reliability or sensitivity measures when considering training interventions has however been recognised, along with small sample sizes (Dos Santos et al., 2019). When selecting an outcome measure it has been suggested that several factors are considered, for example its reproducibility and its responsiveness to change (Smith et al., 2015). Appropriate sample sizes allow studies to be adequately powered. Transparent reporting of sample size estimation allows reproducibility of the calculations made and fair judgement of the findings reported, however recent work indicates this is often lacking in biomechanics studies (Robinson et al., 2021). Detailed consideration of the suitability of the KAM to evaluate interventions is therefore needed.

The KAM is one component of the knee moment vector and is typically smaller in magnitude than the larger sagittal moment component. As a relatively small signal it has been shown to display considerable variability in dynamic tasks (Malfait et al., 2014; Sankey et al., 2015) and it is also likely affected by methodological decisions related to joint axis definition and cross-talk (Benoit et al., 2006), modelling (Robinson et al., 2014) and filtering (Kristianslund et al., 2012). Furthermore, poor reporting of methods, normalisation, and perspective (internal vs external) can also lead to varying moment waveforms (Derrick et al., 2020). The ambiguity with all of these issues means that the suitability of the KAM as a primary outcome measure needs critical evaluation.

In planning an intervention study, it would be prudent to use the primary outcome measure for sample size estimation. If a future intervention wished to observe a reduction in the KAM, effect sizes from prior KAM intervention studies could help to inform a suitable effect size to use in the sample size calculation. Whilst typically sample size estimation is conducted using a peak value (e.g. pKAM), increasingly researchers are interested in evaluating biomechanical waveforms holistically as the KAM waveform contains relevant information about kinematic parameters that are missed if considering the peak KAM only (Sigurðsson et al., 2021). An alternative therefore is to conduct sample size estimation using the whole KAM waveform (i.e. 1-dimensional or waveform-level power analysis and corresponding sample size estimation, Robinson et al., 2021). To conduct waveform-level power analysis and corresponding sample size estimation, a representative KAM waveform and effect size are required. These are used to simulate multiple hypothetical experiments with the desired KAM reduction so that the sample size required to achieve statistical power of 0.8 can be estimated. KAM waveforms are often reported in sidestepping studies and pKAM magnitudes are often reported in intervention studies so these data should be readily available.

It is therefore appropriate to evaluate the KAM as a primary outcome measure for future biomechanical interventions. To achieve this, four aims were set out: (1) to review the reported effect sizes from currently published intervention studies, (2) to summarise their statistical power reporting practices, (3) to collate reported KAM waveforms during sidestepping to establish a typical KAM waveform, (4) to undertake an example waveform-level power analysis to estimate the samples required to observe literature informed KAM reduction during sidestepping for a hypothetical intervention study. Our expectations with respect to each aim were; (Aim 1) we expected within-day effects to be larger than long-term effects, (Aim 2) we expected that power analysis would not be well-reported, (Aim 3) we expected some variation in the KAM waveforms, (Aim 4) we had no prior expectations of sample sizes required.

2. Methods

To achieve the aims set out, a systematic search of Scopus and Web of Science databases was performed to extract papers assessing KAM during sidestep cutting (performed October 2022). Search terms were:

1. “knee” AND
2. “moment”, or “torque” AND
3. “abduct*”, or “adduct*”, or “varus”, or “valgus” AND
4. “cut*”, or “sidestep*”, or “change of direction”

Following this initial search any duplicates were removed. Titles, abstracts and full-texts were manually screened to filter papers for two distinct aims:

(i) those reporting changes in peak KAM as a result of an intervention – to evaluate observed effect sizes and summarise power reporting – Aims 1 and 2
(ii) those displaying a visualisation of the KAM waveform during sidestep cutting – to determine a typical KAM shape – Aim 3

All other papers were removed (Fig. 1).

2.1. Evaluating observed peak KAM effect sizes – aim 1

To understand current effect sizes seen in peak KAM following an intervention, studies reporting a change in KAM were summarised. Two categories of intervention were considered, long-term exercise interventions (lasting four or more weeks), and within-day technique manipulation studies. Eligible papers were categorised into one of these two groups. To be eligible for this aspect, studies had to have reported either a pre to post change in peak KAM following a training intervention or reported peak KAM during two or more technique manipulation conditions. Where results were only reported visually (Dempsey et al., 2007; Ogasawara et al., 2020; Weir et al., 2019), WebPlotDigitizer (v.4.3, https://automeris.io/WebPlot Digitizer) was used to estimate the pre to post changes. It was felt that this could not be accurately achieved in one paper (Smith et al., 2020), therefore this paper was removed from further analysis. Where multiple participant groups were included or where there were multiple conditions, the minimum and maximum effect sizes were selected to indicate the range of changes seen across conditions. It was indicated which conditions were selected to be a part of this comparison and these were then summarised. Where means and standard deviations were reported, or able to be derived, Cohen’s d_{av} effect size was calculated as an appropriate effect size descriptor when repeat measurements are taken from a sample (Lakens, 2013). Effect size interpretations were; 0.2 = small, 0.5 = medium, 0.8 = large (Cohen, 1988).

2.2. Auditing power analysis reporting practice – aim 2

To assess the current reporting practice within this area of the literature, the papers reporting changes in peak KAM were also evaluated in terms of *a priori* power analysis reporting. A full text screen was used to determine firstly how many of these papers reported performing *a priori* power analysis. If power analysis was reported, the details of this were then summarised. Specifically, alpha, beta, the stated effect size, what variable this effect size was based upon, and the source of the effect size.

2.3. Collating knee abduction moment waveforms – aim 3

To perform waveform-level power analysis, a baseline signal is required upon which an alternative effect can be tested. To determine what a typical baseline signal should look like for the KAM during sidestep cutting, a second group of papers were selected from the initial search during the title and abstract screening. These papers were then full text screened to extract papers that met the following criteria (Fig. 1):

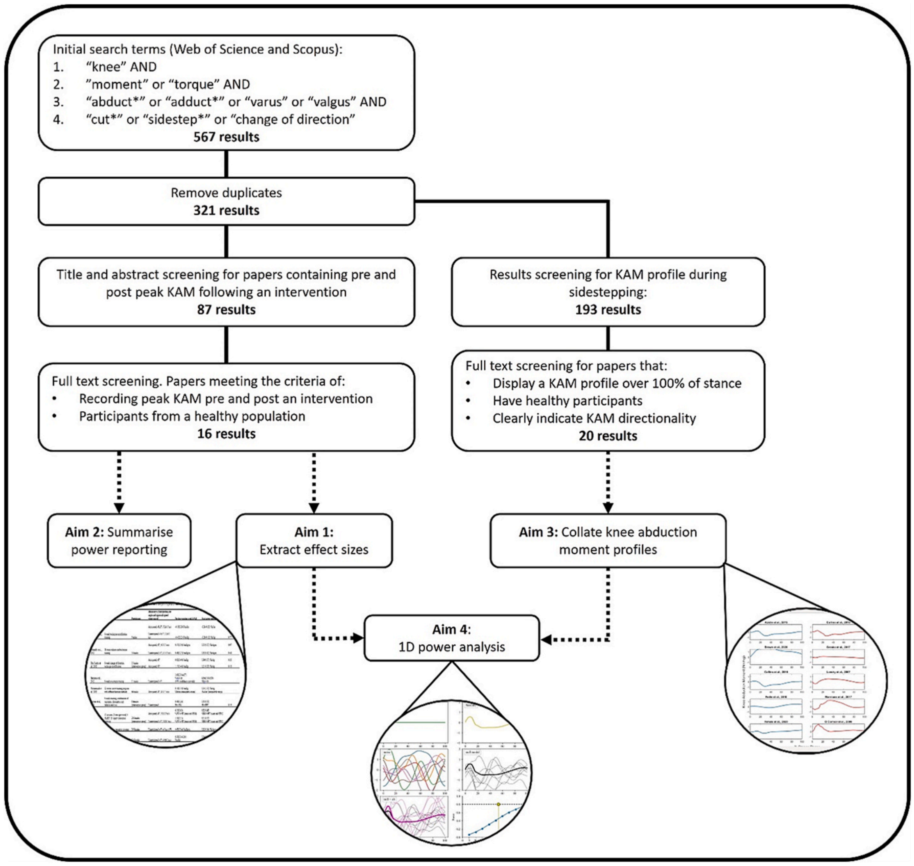

Fig. 1. An overview of the study indicating the different phases of the literature search, search outcomes and aims. For the full criteria used at each phase of screening please refer to the text.

- They displayed a graphical representation of a KAM waveform from a sidestep cut
- Participants used an approach run
- Healthy participants were tested
- Units were clearly displayed
- A clear indication of signal direction (abduction and adduction) was present
- They stated whether an internal or external moment was reported
- The KAM waveform was reported over 100 % of the stance phase

The KAM waveforms from all papers were then digitized using WebPlotDigitizer. Data was then interpolated to 101 points. Where multiple plots were presented within the same paper, only one was selected. Where different directions of signal were reported, these were all converted to follow the same convention (external moments with knee abduction represented positively). Similarly, where plots were digitized in different units, they were normalized using the reported participant body mass, converting them all to Nm·kg^{-1}. Once all waveforms were similarly formatted to allow comparison the digitized KAM signal from each paper was plotted to visualise a typical KAM waveform during sidestep cutting. We did not exclude waveforms based on factors such as sex or anticipation condition. Full details of the KAM waveforms and experimental contexts can be found in Table S1.

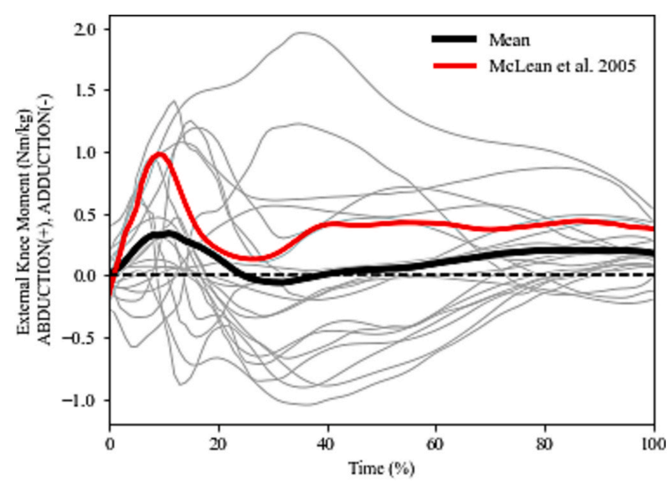

Fig. 2. All knee abduction moment waveforms (grey lines). The mean KAM waveform is shown as the black thick line. The moment waveform of McLean et al. (2005) is shown in red and used as the baseline waveform for subsequent waveform-level power analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.4. Future sample size estimation – aim 4

Waveform-level power analysis was conducted using power1D (v.0.1.1, https://github.com/power1d; Pataky, 2017) in Python. As there was no clear consensus regarding a typical baseline waveform for KAM during sidestep cutting, a single waveform (McLean et al., 2005) that had similar temporal characteristics as the mean waveform (see Fig. 2) was selected for use in sample size estimation. The process of waveform-level power calculation and corresponding sample size estimation has been described previously (Robinson et al., 2021) and is summarised in brief as follows. To create realistic alternative hypotheses to the baseline signal i.e. a reduction in the KAM, a negative Gaussian pulse was generated based on the median effect sizes for each intervention type from Tables 1 and 2 (Fig. 3a). 1-dimensional random noise

Table 1
Reported changes in peak KAM from long-term interventions. KAM results are means and standard deviations unless otherwise specified.

	Intervention	Participants	Manoeuvre (Anticipation, cut angle and approach/cut velocity – where stated)	Pre intervention peak KAM	Post intervention peak KAM	Effect size (Cohens d_{av})
Dempsey et al., 2009	6-week technique modification training	9 males	Anticipated, 45 ± 5°, 5.2 ± 0.5 m·s^{-1}	−0.38 (0.26) Nm·kg^{-1}·m^{-1}	−0.24 (0.22) Nm·kg^{-1}·m^{-1}	0.58
			Unanticipated, 45 ± 5°, 5.2 ± 0.5 m·s^{-1}	−0.40 (0.23) Nm·kg^{-1}·m^{-1}	−0.26 (0.11) Nm·kg^{-1}·m^{-1}	0.82
Dix et al., 2021	1 season of completing the 11 + as a warm up to	31 females (dom. leg)	Anticipated, 90°, 3.15 ± 0.41 m·s^{-1} (pre), 3.18 ± 0.46 m·s^{-1} (post)	0.24 (0.12) Nm·kg^{-1}·m^{-1}	0.25 (0.12) Nm·kg^{-1}·m^{-1}	0.08
Donnelly et al., 2012	28-week balance and technique training	34 males	Anticipated, 45°, 4.5–5.5 m·s^{-1}	0.37 (0.30) Nm·kg^{-1}·m^{-1}	0.35 (0.27) Nm·kg^{-1}·m^{-1}	0.07
			Unanticipated, 45°, 4.5–5.5 m·s^{-1}	0.48 (0.27) Nm·kg^{-1}·m^{-1}	0.63 (0.40) Nm·kg^{-1}·m^{-1}	0.45
Dos Santos et al., 2021	6-week change of direction technique modification	15 males (INT group)	Anticipated, 45°, "as fast as possible" 5.08 ± 0.29 m·s^{-1} (pre); 5.41 ± 0.29 m·s^{-1} (post)	0.82 (0.49) Nm·kg^{-1}	0.90 (0.27) Nm·kg^{-1}	0.21
			Anticipated, 90°, "as fast as possible" 3.41 ± 0.27 m·s^{-1} (pre); 3.47 ± 0.32 m·s^{-1} (post)	1.17 (0.46) Nm·kg^{-1}	1.11 (0.29) Nm·kg^{-1}	0.16
Jamison et al., 2012	6-weeks resistance training	11 males (RT group)	Unanticipated, 45°, "self-selected jogging speed"	3.03 (2.10–4.37) %BW x HT (Mean + 95 % CI)	4.56 (3.00–6.90) %BW x HT (Mean + 95 % CI)	
Mohammadi Orangi et al., 2021	12-weeks soccer training program with different learning methods	66 males	Anticipated, 45°, 4.5–5.5 m·s^{-1}	0.16 (1.34) Nm·kg^{-1}Median (IQR)	0.14 (1.53) Nm·kg^{-1}Median (IQR)	
Mornieux et al., 2021	5-week core strengthening program	19 females	Unanticipated, 45°, 4 ± 0.2 m·s^{-1}	0.74 (0.45) Nm·kg^{-1}	0.71 (0.48) Nm·kg^{-1}	0.06
Staynor et al., 2017	9-weeks training, combination of resistance, plyometrics and balance exercises	8 females (INT group)	Unanticipated	0.49 (0.26) HT x BW	0.45 (0.23) HT x BW	0.16
Thompson et al., 2017	15 sessions (2 times per week) F-MARC 11 + injury prevention warm up	28 females (INT group)	Anticipated, 45°, 3.8 ± 0.5 m·s^{-1}	6.15 (3.33) %BW x HT	6.82 (2.45) %BW x HT	0.23
			Unanticipated, 45°, 3.8 ± 0.5 m·s^{-1}	5.51 (2.70) %BW x HT	6.51 (2.55) %BW x HT	0.38
Weir et al., 2019	9-week injury prevention program	26 females	Unanticipated, 45°, 4.5 m·s^{-1} ± 5 %	0.65(0.34)* Nm·kg^{-1}·m^{-1}	0.62(0.34)* Nm·kg^{-1}·m^{-1}	0.09
Weltin et al., 2017	4-weeks perturbation and plyometric training	12 females	Unanticipated, 45°, 4.0 ± 0.2 m·s^{-1}	0.39(0.14–0.64) Nm·kg^{-1} Median (IQR)	0.34(0.16–0.52) Nm·kg^{-1}Median (IQR)	

*estimated from visual presentation of the data using WebPlotDigitizer.

Table 2
Reported changes in peak KAM from studies investigating within-day technique manipulations.

	Comparison	Participants	Target Manoeuvre (Anticipation, cut angle and approach speed where stated)	Condition 1 peak KAM	Condition 2 peak KAM	Effect Size (Cohens d)
Chaudhari et al., 2005	Compared different sporting postures to baseline	11 participants (6 females, 5 males)	Anticipated, 90°, "speed that allowed them to plant their foot straight ahead, face forward, and still cut as close to laterally as possible"	Baseline 2.8 (2.9) %BW x ht	Lacrosse posture 4.5 (1.8) %BW x ht	0.72
					Holding football to the cut side2.9 (2.6) %BW x ht	0.04
Cortes et al., 2012	Forefoot and rearfoot strike	22 females	Unanticipated, 45° (35–55), >3.5 m·s^{-1}	Rearfoot0.41 (0.3) Nm·kg^{-1}·m^{-1}	Forefoot0.34 (0.3) Nm·kg^{-1}·m^{-1}	0.23
Dempsey et al., 2007	Technique modification compared to baseline	15 males	Anticipated, 45 ± 5°, 4.5 ± 0.2 m·s^{-1}	Baseline0.45 (0.32) Nm·kg^{-1}·m^{-1}	Foot wide technique0.79(0.38) Nm·kg^{-1}·m^{-1}	0.97
					Torso leaning in same direction 0.47 (0.36) Nm·kg^{-1}·m^{-1}	0.06
Nishizawa et al., 2022	Foot progression angle changes	19 males	45°, "sprint as fast as they can and then performed a 45-degree side cutting task to the side opposite to the tested limb at a self-selected speed"	Toe Neutral at peak Fz −0.6 (0.80)	Toe In at peak Fz0.6 (1.2) Nm·kg^{-1}	1.2
Ogasawara et al., 2020	Forefoot and rearfoot strike	24 females	Anticipated, 60°, <2.0 m·s^{-1}	Rearfoot −0.33(0.21)* Nm·kg^{-1}	Forefoot −0.30(0.16)* Nm·kg^{-1}	0.16

*estimated from visual presentation of the data using WebPlotDigitizer.

was then combined to create alternative models for each effect size (Fig. 3b). Smooth Gaussian noise was selected for this dataset, with a standard deviation of 0.352 Nm/kg (calculated from McLean et al., 2005), and full width half maximum of 20 as this is a good estimate of the smoothness within biomechanical data (Pataky et al., 2016). Multiple simulated experiments (n = 5000) were conducted to establish omnibus power across a range of sample sizes from 25 to 500. This was used to determine the minimum sample size needed for each median

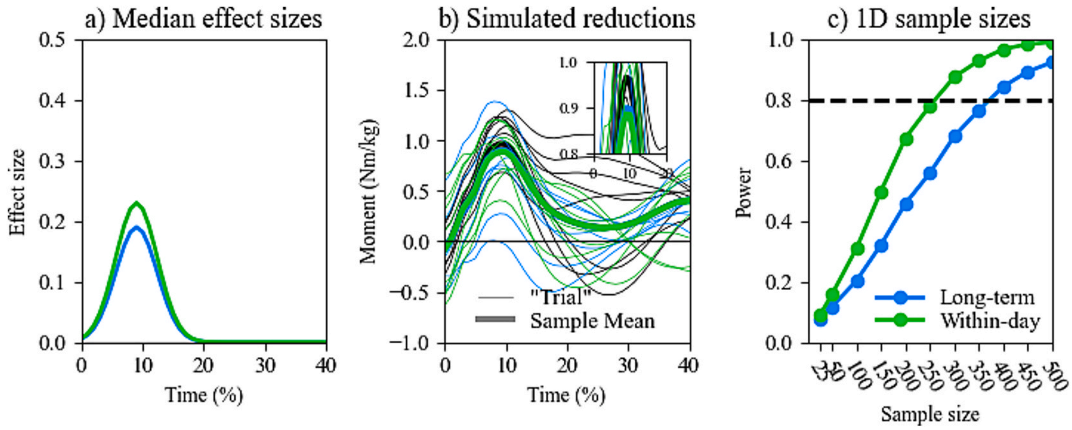

Fig. 3. Waveform-level power analysis for the median effect sizes observed during long term training interventions and within day technique manipulations. (a) The median effect sizes tested. (b) Effect size reductions applied to the relevant signal with noise. Thick lines represent the mean for each effect size with the black line being the baseline signal. (b-inset) a rescaled view of the effect size reductions with respect to the baseline signal (c) the statistical power achieved in the hypothetical experiments over a range of sample sizes.

effect size tested to achieve a power of 0.8 (Fig. 3c).

3. Results

3.1. Evaluating observed peak KAM effect sizes

Changes in peak KAM for the long-term training intervention (Table 1) and within-day technique manipulation papers (Table 2) are reported. 11 studies reported pre to post changes in KAM following a long-term intervention. Calculated effect sizes ranged from 0.06 to 0.82 with the median effect size being 0.19. Five studies reported changes in KAM during sidestep cutting during within-day technique manipulations. Effect sizes ranged from 0.04 to 1.7 with the median effect size being 0.23.

3.2. Auditing power analysis reporting practice

Power analysis reporting practice was mixed among the studies investigating both the long-term training interventions (Table 3) and the within-day technique manipulations (Table 4). Of the 11 papers recording pre to post changes in peak knee abduction following an exercise training intervention, 3 did not report *a priori* power analysis. Only 3 papers had a replicable sample size estimation (Dix et al., 2021; Dos Santos et al., 2021; Mornieux et al., 2021). Of the 5 within-day technique manipulation papers recording changes in peak knee abduction, 1 did not record performing *a priori* power analysis and 1 was replicable (Nishizawa et al., 2022). Across both categories common practices involved reporting *a priori* sample size estimations, but not providing all of the parameters required to replicate these calculations.

3.3. Collating knee abduction moment waveforms

Digitized waveforms are presented in Fig. 2. Full detail of the papers included can be found in Table S1 within the Supplementary Material.

3.4. Waveform-level power analysis

Waveform-level power analysis was conducted on the waveform digitized from the work of McLean and colleagues (2005) for the median effect sizes 0.16 for the long-term interventions and 0.23 for within-day interventions (Fig. 3). The estimated sample sizes needed to achieve a power of 0.8 were ~360 for the long-term interventions and ~255 for within-day interventions.

4. Discussion

This study reviewed reported peak KAM effect sizes and power reporting practice from biomechanical intervention studies, collated KAM waveforms from sidestepping studies and simulated the KAM response to a hypothetical intervention based on the median effect sizes observed. The KAM effect sizes reported pre to post a long-term training intervention varied from small (0.06) to large (0.82). Medium-large effect sizes tended to be observed in unanticipated sidestepping which likely further underlines the importance of ecological validity within biomechanical assessment (Bolt et al., 2021). Within day technique manipulations elicited the largest effect sizes. Observed effect sizes for within day technique manipulations ranged from small (0.04) to large (1.2). Within day assessment avoids the additional errors of inter-session sidestepping assessment (Sankey et al., 2015). Notably within-day technique modification training interventions tended to observe larger KAM effect sizes than general injury prevention or strength training. Some variation in effect size distribution is to be expected as all interventions differed in the duration and activities prescribed. A key challenge when planning future interventions is identifying characteristics that made previous interventions effective (such as study design, relevant outcomes / interventions chosen, standardisation of tasks, methods, cohorts) so that these elements can be replicated and built upon. Some caution should be used when judging the magnitudes of effect sizes as it might be expected that these effect sizes overestimate the true KAM effect size due to publication bias (Lakens, 2013). All interventions aimed to reduce ACL injury risk, which meant a reduction in the KAM was targeted. Not all studies found a reduction in the KAM as there were both increases and decreases in peak KAM observed. The lack of consistency in the direction of the change of the KAM (reproducibility) and the relatively small effect sizes observed (responsiveness to change) both undermine the choice of KAM as a primary outcome measure for a training intervention (Smith et al., 2015). This of course does not preclude the KAM being chosen as an intervention target, but it may be difficult to justify without careful data and quality assurance processes. This has been corroborated independently by a recent *meta*-analysis of injury prevention randomised control trials, where five studies reporting KAM outcomes showed serious risk of bias, imprecision and a low certainty of evidence (Lima et al., 2024).

There was a lack of consistency in power analysis reporting practice. Several papers did not report a sample size estimation and those that did often failed to report the effect size considered, the variable that they had based their calculations on, or their justification of these choices. This was not unexpected as similar issues with power analysis reporting have been demonstrated in biomechanics and sports science studies

Table 3
Power analysis reporting practice of the papers investigating pre to post changes in peak KAM following a long-term intervention.

	Power analysis reported?	Power Alpha	Effect size stated	Effect size variable	Source
Dempsey et al., 2009	Yes	0.8 power, 0.05 alpha	unknown	unknown	Previous research (Besier et al., 2001)
Dix et al., 2021	Yes	0.8 power, 0.05 alpha	0.65 (calculated)	Knee abduction angle	Pilot work
Donnelly et al., 2012	No	n/a	n/a	n/a	n/a
Dos Santos et al., 2021	Yes	0.8 power, 0.05 alpha	0.73	Pre to post changes in peak KAM during 180° turning	Previous research (Jones et al., 2015)
Jamison et al., 2012	Yes	0.8 power, 0.025 alpha	1.0	Peak KAM and tibial internal rotation moments	unknown
Mohammadi Orangi et al., 2021	No	n/a	n/a	n/a	n/a
Mornieux et al., 2021	Yes	0.8 power, 0.05 alpha	0.6	Trunk kinematic data	Previous research (Weltin et al., 2017)
Staynor et al., 2017	Yes	0.8 power, 0.05 alpha	0.78	unknown	Previous research (Dempsey et al., 2009)
Thompson et al., 2017	No	n/a	n/a	n/a	n/a
Weir et al., 2019	Yes	0.8 power, 0.05 alpha	unknown	Changes in peak KAM and muscle activation	Previous research (Donnelly et al., 2015; Myer et al., 2005; Myer et al., 2008)
Weltin et al., 2017	Yes	0.8 power, 0.05 alpha	unknown	unknown	Previous research (Mornieux et al., 2014)

previously (Abt et al., 2020; McCrum et al., 2022; Robinson et al., 2021). It does however hinder reproducibility and makes it difficult to determine if studies are sufficiently powered. In the studies that reported the variable used it should be noted that not all studies chose the KAM as the input variable for sample size estimation, others used the knee abduction angle or trunk kinematics. Using the knee abduction angle for power analysis may also be problematic based on between study heterogeneity, inconsistency and imprecision (Lima et al., 2024). Finally, the effect sizes used for sample size estimation were often larger than the effect sizes observed in the results, demonstrating perhaps an overly optimistic *a-priori* perception of the likely effect of an intervention on biomechanical parameters. Effect sizes from *meta*-analyses (e.g. Lima et al., 2024) are generally preferred to inform sample size estimation over those from a single previous study, though ultimately there are a variety of approaches to justify sample sizes and whichever approach is chosen should be considered and justified carefully (Lakens, 2022).

We attempted to establish a representative KAM waveform from existing sidestepping studies. This was not a trivial task as there is considerable variation in the quality of the description of the joint moments calculated, and failing to specify whether internal or external moments were being reported meant some studies had to be excluded. Clearer reporting standards should be encouraged (Derrick et al., 2020). When overlaying waveforms from studies visually reporting the KAM, there was considerable variation in the waveform characteristics (e.g. peaks, moment directions and magnitudes). Some of this variation can be explained by the lack of a standardised sidestepping protocol, as the range of approach speeds varied from 3 to 7 $m \cdot s^{-1}$, cut angle varied between 35 and 90° and cut direction was either anticipated or unanticipated, all of which are known to affect the KAM (Brown et al., 2014; Dos Santos et al., 2018; Vanrenterghem et al., 2012). The lack of a clear overall moment waveform, particularly after initial weight acceptance (>~20 % stance) further highlights the variability of the KAM waveform. Full details of study participants, anticipation status, cut angle, approach speed and conditions chosen are provided in Supplementary Material (Table S1) as well as separation of waveforms by anticipation condition (Fig. S1) and by similar angles and approach speeds (Fig. S2) for completeness. With a strict range of approach speeds (4–5.5 $m \cdot s^{-1}$) and a target cutting angle of 45° there was a more consistent waveform found (Fig. S2). It may be worth standardising these parameters if studies wish to make predictions with respect to the KAM shape, for example a reduction in the KAM during weight acceptance. Alternatively, it may be more prudent to target the non-sagittal moment vector (frontal and transverse plane combined) for intervention as an axis independent measure which may reduce some variation caused by moment axis definition (Robinson et al., 2023).

We used median effect sizes and the KAM waveform from previous studies to perform waveform-level power analysis and corresponding sample size estimations for hypothetical long-term and within-day interventions. The estimated sample sizes of ~360 for the long-term interventions and ~255 for within-day interventions far exceeded the range of sample sizes used to evaluate interventions to date. Similar sample size estimations using example datasets conducted by Robinson et al. (2021) have shown waveform-level analysis to require more samples to achieve the same power as would be yielded from a power analysis conducted on simple scalar data. The waveform-level power

Table 4
Power analysis reporting practice of the papers investigating changes in peak KAM from a within-day technique manipulations.

	Power analysis reported?	Power Alpha	Effect size stated	Effect size variable	Source
Chaudhari et al., 2005	No	n/a	n/a	n/a	n/a
Cortes et al., 2012	Yes	0.8 power 0.05 alpha	unknown	unknown	Previous research (Greig, 2009; McLean et al., 2005)
Dempsey et al., 2007	Yes	0.8 power 0.05 alpha	0.65	unknown	Previous research (Besier et al., 2001)
Nishizawa et al., 2022	Yes	0.8 power, 0.05 alpha	0.58 (calculated)	Knee abduction angle	Previous research (Sakurai et al., 2020)
Ogasawara et al., 2020	Yes	0.95 power 0.01 alpha	0.3	unknown	unknown

calculation considers the probability of rejecting the null hypothesis at any point along the waveform and therefore requires more samples. However, differences in waveform-level vs. simple scalar power analysis reported in Robinson et al. (2021) are insufficient to explain the discrepancy between common sample size practice and the very large sample sizes (>250) that we estimated in this study. This does not mean that intervention studies cannot have high statistical power or significant KAM reductions with fewer participants than the median effect size estimated. The high estimated sample sizes highlight the challenge of planning future intervention studies when KAM outcomes are variable and inconsistent. As sample size estimation is ultimately determined by the input variables it seems difficult to justify alternative parameters to the median effect size and the representative standard deviation used. A larger effect size would reduce the required samples but not represent the range of effects observed. Similarly, reducing the standard deviation used would reduce the required samples but then would not represent the variation in the KAM measured experimentally. Ultimately a smaller effect size is going to require a greater number of samples to power an intervention study appropriately. This study highlights the challenge of powering studies appropriately using the KAM as the primary outcome measure.

Using 1-dimensional power analysis is more challenging to a researcher and requires both an effect size of interest and baseline KAM waveform to be defined (Pataky et al., 2018). This study outlines the challenges of this. Future work could consider defining the smallest effect size of interest prior to data collection. For the case of long-term training interventions or within-day technique manipulations it seems logical to define what would be a worthwhile successful intervention and what would be deemed negligible. This is problematic when KAM is used as an outcome measure, as there is a lack of evidence defining what an 'at risk' and 'safe' KAM is during sidestep cutting. Until this is established, it is difficult for researchers to determine whether a training intervention can be deemed successful when considering KAM as an outcome measure. As an alternative, the knee flexion angle is arguably a more reliable measure, but current evidence provides little certainty that injury prevention programmes can have an impact on this parameter (Lima et al., 2024).

Limitations of this study include not being able to calculate standardised effect sizes from all relevant intervention studies. Also, in some studies with multiple conditions we had to make a decision about which condition to plot to avoid having more than one KAM waveform per study. We also deliberately did not separate out KAM waveforms by variables that are known to influence them. We have however provided all relevant choices and details from these (Table S1) and figures (Figs. S1 and S2) that separate KAM waveforms in the Supplementary Material. Furthermore, the requirements to digitise some KAM waveforms manually inherently introduces some degree of error, but this is likely negligible in comparison to the variability between waveforms. Specific parameter decisions for waveform-level power analysis and corresponding sample size calculations which include the chosen representative waveform, standard deviations and noise model will all influence the sample sizes estimated. These results are synthesized across a variety of different interventions and do not therefore reflect the effectiveness of a single intervention. Instead, we provided broad consideration of the suitability of the KAM, during sidestepping, across evidence from a range of interventions and so results should be considered in this generic context.

5. Conclusion

Intervention studies evaluating the KAM during sidestepping showed inconsistent reporting of power analysis and the peak KAM showed variable effect sizes. A representative KAM waveform during sidestepping was difficult to establish from the published literature. When conducting a hypothetical sample size estimation for a KAM reduction, resulting sample sizes appeared prohibitive. Conducting robustly powered interventions is therefore challenging due to inconsistent effect sizes and waveforms. Critical reflection on the suitability of the KAM as a primary outcome measure is required to reduce unnecessary variation from inter-lab (in)consistencies and to improve standardisation of sidestepping protocols. Without this, interventions to reduce knee injury risk are better not founded on the reduction of KAM observed during sidestepping.

CRediT authorship contribution statement

Hazel Tucker: Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation. **Jos Vanrenterghem:** Writing – review & editing, Conceptualization. **Todd C. Pataky:** Writing – review & editing, Conceptualization. **Mark A. Robinson:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2025.112896.

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