Published in final edited form as:

Br J Sports Med. 2014 March ; 48(6): 464–468. doi:10.1136/bjsports-2012-091398.

The ‘impact’ of force filtering cut-off frequency on the peak knee abduction moment during landing: artefact or ‘artifiction’?

Benjamin D Roewer¹, Kevin R Ford^{2,3}, Gregory D Myer^{1,4}, and Timothy E Hewett^{1,4}

¹Sports Health and Performance Institute, The Ohio State University, Columbus, Ohio, USA

²Division of Sports Medicine, Cincinnati Children’s Hospital Medical Center, Cincinnati, Ohio, USA

³Department of Pediatrics and Orthopaedic Surgery, College of Medicine, University of Cincinnati, Cincinnati, Ohio, USA

⁴Departments of Physiology and Cell Biology, Orthopaedic Surgery, Family Medicine, Biomedical Engineering and The School of Health and Rehabilitation Sciences, The Ohio State University, Columbus, Ohio, USA

Abstract

Background—Joint moments computed using inverse dynamic techniques are important estimators of net joint loads. Joint moments computed from marker position and ground reaction force data filtered using different cut-off frequencies may capture changes in moment magnitudes at a single joint that exceed normal physiological response. Peak external knee abduction moment (KAM) generated during landing (ie, the drop vertical jump, DVJ) predicts anterior cruciate ligament injury risk using marker and force data filtered at different cut-off frequencies. The purpose of the current investigation was to determine the effects of using the same low cut-off frequencies versus different cut-off frequencies on joint moment magnitudes to evaluate if artificial smoothing attenuates actual resultant joint loads related to injury risk.

Methods—Twenty-two female, high school volleyball players performed three maximum DVJs in a laboratory setting. The average peak KAM was computed for each knee using marker and force data filtered with the same low cut-off frequencies and different cut-off frequencies.

Results—Peak KAMs were significantly larger using different cut-off frequencies. The order of athletes ranked based on the magnitude of their peak KAMs did not significantly change across all filtering cut-off frequencies.

Conclusions—The magnitude of peak KAM may differ when the same low or different higher cut-off frequencies are used to filter marker and ground reaction forces (GRF) data collected using standard motion capture equipment. It is not clear to what extent the decrease in peak KAM

Copyright Article author (or their employer) 2012.

Correspondence to: Benjamin David Roewer, Sports Health and Performance Institute, The Ohio State University, 2050 Kenny Road, Suite 3100, Columbus, OH 43221, USA; Ben.Roewer@osumc.edu.

Contributors All authors have contributed to either the design or execution of this study or analysis of the findings from this study. All authors have approved the final submitted version of the research manuscript.

Provenance and peer review Not commissioned; externally peer reviewed.

reported when the same low cut-off frequencies were used was solely due to attenuation of the GRF signal.

INTRODUCTION

Rupture of the anterior cruciate ligament (ACL) is a devastating knee injury that disproportionately afflicts young female athletes who participate in running, cutting and jumping sports relative to their male counterparts.¹ ACL injury leads to loss of playing time, a higher likelihood of developing knee osteoarthritis² and often requires surgery to restore mechanical stability and long-term rehabilitation focused on functional restoration before an athlete can return to a high level of competition. Despite restoring passive stability in the knee, nearly two-thirds of competitive-level athletes do not return to their previous level of play within 1 year following ACL reconstruction,³ and those who do may have between a one in four or one in five chance of suffering a subsequent ACL injury within the first year following surgery.⁴

The primary causative factors that increase the risk for ACL injury have not been discretely elucidated, but they likely include a combination of anatomical,⁵ biomechanical,⁶ neuromuscular,^{7,8} hormonal⁹ and genetic¹⁰ factors. Particular emphasis has been placed on identification of the biomechanical and neuromuscular risk factors that may predict future ACL injury, as these factors have been shown to be modifiable through supervised training programmes.^{11,12}

Knee abduction moment (KAM) is currently the strongest reported single predictor of primary ACL injury in young female athletes, with a sensitivity of 78% and a specificity of 73%.⁶ However, using this biomechanical predictor to identify young athletes at risk of ACL injuries requires the ability to accurately measure joint moments using inverse dynamic techniques. For example, during a drop vertical jump (DVJ), a subject is outfitted with reflective markers to track the motion of the limbs and force plates are used to measure the forces that act upon the subject's body during contact with the ground. The inertial properties and relative motions of the body segments are used in conjunction with the measured ground reaction forces (GRFs) to calculate the net moments acting about each joint. Invariably, this technique is subject to high-frequency noise due to skin artefacts and vibrations during foot-to-ground contact. For these and other reasons, marker position and GRF data are low-pass filtered to remove high-frequency noise prior to calculation of joint moments. In theory, exceedingly large joint moments may be observed if marker position and GRF data are low-pass filtered using different cut-off frequencies,¹³ but this likely depends on the task being evaluated.

Joint moment artefacts are particularly problematic during rapid, high-load movements such as side-step cutting, during which large GRF impact peaks and segment accelerations are observed. A recent report indicated that significantly larger peak KAMs were observed during a sidestep cut when different cut-off frequencies were applied to marker and GRF data (eg, 10 and 50 Hz, respectively) compared to when the same cut-off frequencies were applied (eg, 10 and 10 Hz, respectively).¹⁴ The authors purported that the larger peak KAM values must have contained large artefacts because they were calculated using marker and

GRF data that were filtered at different frequencies. These authors may have over-extended their conclusions when they argued that findings from studies that used different marker position and GRF cut-off frequencies should be reconsidered. These authors speculated that their findings from a sidestep cut task data apply directly to a landing task, such as a DVJ landing, even though the timing of peak KAM, and the motion of the limbs and the magnitude of the GRFs differ greatly between tasks.¹⁵ As mentioned, KAM generated during landing of a DVJ predicts ACL injury risk with high sensitivity and specificity using marker and GRF data filtered at different cut-off frequencies. Therefore, the purpose of the current investigation was to determine the effects of using the same low cut-off frequencies versus using different cut-off frequencies to filter marker and GRF on joint moment magnitudes during the DVJ to evaluate if artificial smoothing attenuates actual resultant joint loads related to injury risk.

METHODS

Subject sample

Twenty-two female high-school volleyball players (height= 168.8±4.5 cm, mass=63.1±8.1 kg, age=15.4±1.0 years) were tested prior to the onset of their sport season. Each subject provided informed consent approved by the Ohio State University institutional review board. Subject height (cm) was measured using a stadiometer, body mass (kg) was measured using a calibrated scale (Tanita Corporation, Japan) and maximum vertical jump height (in) was measured by recording the maximum height each subject reached during three vertical leap attempts against a wall-mounted measuring tape.

Drop vertical jump procedures

Forty-three, 9 mm retro-reflective markers were placed on the sacrum, C7, left PSIS, sternum and bilaterally on the shoulders, elbows, wrists, ASIS, greater trochanter, mid-thigh, medial and lateral knee joint line, tibial tubercle, lateral shank, distal shank, medial and lateral ankle, heel, dorsal surface of the mid foot, fifth metatarsal and toe. Each subject wore a small, modified backpack also outfitted with three retro-reflective markers placed non-collinearly. A static calibration trial was collected with the subject standing in a neutral pose and facing a principal axis of the lab coordinate system. Each subject received standardised instructions and was given three practice jump attempts to become familiar with the task prior to recording data. Subjects were instructed to drop from a 31 cm tall box, land with both feet making isolated contact with two force plates embedded in the laboratory floor (Bertec Corp. Worthington, Ohio, USA), and subsequently perform a maximal vertical jump, reaching up towards the overhead target with both hands.⁶¹⁶ An overhead target was placed above the force plate at the subject's recorded maximum vertical jump height. Each subject performed three DVJ trials. Trials were accepted if the participant dropped from the box and their feet made simultaneous and isolated contact with the force plates. Three-dimensional marker position data were sampled at 240 Hz using eight infrared cameras (Vicon, Oxford Metric Ltd, London, UK), and ground reaction force data were sampled at 1200 Hz.

Data analysis

Data were processed using custom Visual 3D (C-motion Inc, Germantown, Maryland, USA) and Matlab (Mathworks Inc, Natick, Massachusetts, USA) coding. Initial contact (IC) and take-off (TO) events were defined when the vertical component of the unfiltered GRF exceeded and fell below 10N, respectively. Gaps in marker position data fewer than 25 frames (ie, 1/10th second or less) were interpolated using a cubic spline fill. Hip joint centres were computed using the technique described by Bell *et al.*¹⁷ Knee and ankle joint centres were estimated to be the midpoint between the medial and lateral knee joint line markers, and the medial and lateral ankle markers, respectively. All data were time normalised to 101 points of stance (IC-TO). Peak external KAM during stance was computed and averaged across the three trials for each subject.

Marker and force data were low-pass filtered at the same low cut-off frequency (10, 12 and 15 Hz) and also at different cut-off frequencies (10–50, 12–50 and 15–50 Hz, respectively) using a bidirectional Butterworth filter described previously.¹⁶

Statistical analysis

Analysis of variance (ANOVA) with repeated measures (limb by filter cut-off frequency combination) was used to test for differences in peak KAM measured during 100% of stance of the DVJ using SPSS statistical package (SPSS Inc V.19, Chicago, Illinois, USA). An initial ANOVA indicated no effect of limb ($p=0.05$), so data for both limbs were collapsed and the 44 subject-legs were analysed. Spearman rank correlation was used to test the effect of low-pass filtering conditions on the order of athletes ranked by their peak KAMs computed during stance of the DVJ. A priori significance was set at $\alpha<0.05$ for all tests.

RESULTS

The repeated measures ANOVA indicated a main effect of cut-off frequency combination on peak KAM during 100% of stance for the DVJ ($p<0.001$). Significant differences in peak KAM were detected among all conditions in which the same cut-off frequencies were applied to marker and GRF data ($p<0.01$), but no differences were detected among all conditions in which different cut-off frequencies were applied ($p<0.01$) (table 1).

The average peak KAM values computed using different marker and GRF cut-off frequencies were larger than the peak KAM values computed using the same cut-off frequencies ($p<0.001$; figure 1).

The effect of applying different cut-off frequencies to marker and GRF data was not consistent across all subjects. Large KAM values were not observed near initial contact when the same low cut-off frequencies were applied. However, when different cut-off frequencies were applied some individuals had large KAM values near initial contact (figure 2B), while others did not (figure 2A).

The rank order of KAM values computed using different marker and GRF cut-off frequencies significantly covaried with the order of peak KAM values computed using the same cut-off frequencies in all instances (table 1). In other words, the athletes who had the

largest peak KAM values when the same cut-off frequencies were applied also had the largest peak KAMs when different cut-off frequencies were applied ($p < 0.05$). Seventeen of the 22 subjects in this study were identified as being 'at risk' for future ACL injury using 10 and 50 Hz cut-off frequencies because one or more of their knees exceeded the reported 25.25 Nm peak KAM threshold¹⁸ (figure 3). Three of those 17 subjects were not identified as being 'at risk' using the same low cut-off frequencies.

DISCUSSION

The purpose of this current investigation was to evaluate the effects of applying the same low cut-off frequencies and different cut-off frequencies to marker and GRF data on joint moments calculated using inverse dynamics. Specifically, we aimed to explore the effects of different filtering conditions on the peak KAM computed during a DVJ; a highly sensitive and specific predictor of ACL injury.⁶¹² The current analyses indicated that there were differences between peak KAM computed using marker and GRF data filtered with the same low cut-off frequencies and peak KAM computed using data filtered with different cut-off frequencies; however, the effects of these filtering conditions were not consistent across all subjects. Peak KAM values for some subjects showed a marked effect of using different cut-off frequencies (figure 2B) while others showed nearly no effect (figure 2A).

If peak KAM values for some subjects were significantly affected by filtering condition and others were not, then this poses an interesting and important question: are the peak KAM values obtained when marker and force data are filtered using different frequencies random artefacts or are they real moments? This question is particularly important when using KAM to screen an athlete for ACL injury risk. For example, if the peak KAM computed using GRF data filtered at a high cut-off frequency is an accurate representation of the net frontal-plane knee joint loads, then applying a low cut-off frequency to both marker and force data (eg, 12 Hz) will remove valuable GRF information and lead to erroneous prediction of injury risk. For example, three of the 17 subjects who had peak KAMs that placed them in the 'at risk' category when different cut-off frequencies were applied (ie, 10–50 Hz) were not identified as being 'at risk' when the same low cut-off frequencies were applied. Conversely, all athletes who were identified as being 'at risk' when the same low cut-off frequencies were applied were also deemed as being 'at risk' when different cut-off frequencies were applied. To date, no published studies have prospectively evaluated ACL injury risk using peak KAM computed from marker and GRF data that were filtered using the same cut-off frequencies. Peak KAM measured using different cut-off frequencies are the only data that have demonstrated positive ACL injury prediction value.⁶

It is arguably more prudent to intervene with all athletes who are identified as being at risk of ACL injury based on data that were filtered using different cut-off frequencies than to not treat athletes who are deemed to not be at risk when determined using the same low cut-off frequencies (ie, false negatives). The direct financial costs of repairing an isolated ACL rupture typically range from \$3000 to \$5000 per procedure,¹⁹ and the costs of revision ACL reconstruction to repair a torn graft may exceed \$20 000 per procedure.¹⁹ These estimates do not factor in postoperative rehabilitation, the costs to repair concomitant injuries sustained during ACL rupture or to treat long-term sequelae.

The cut-off frequency when filtering marker data is selected by choosing the highest frequency that will filter out random noise and skin artefacts while preserving accurate marker coordinate locations. Determining the appropriate low-pass marker cut-off value is achieved through residual analysis or related methods.²⁰ For level walking and even more dynamic joint loading tasks such as landing and cutting⁶²¹²² marker data are typically filtered using a cut-off frequency lower than 20 Hz. Applying the same low cut-off frequency to GRF data will attenuate the signal and remove the true GRF impact peak that appears during rapid, high-impact movements like a landing or a sidestep cut. This GRF impact peak contains large forces that are quickly transmitted from the ground through the foot,²³ and must be absorbed, redirected and converted by the active (muscles) and passive (bones, ligaments and tendons) structures in the body. Even though these impact peaks may lead to joint moments that appear quite large these are real forces being acted upon the body and one should be extremely cautious before filtering them out using a low GRF cut-off frequency in an effort to produce ‘smoother’ joint moment curves.

Marker location and GRF data filtered with progressively smaller cut-off frequencies will produce smoother time-series curves at a cost of removing physiological information.²⁰ Ideally, marker and GRF data should be filtered at the highest frequencies that will remove noise and leave as much physiological signal information intact. Unfortunately, current motion analysis techniques are limited because retro-reflective markers have a small amount of mass, and when placed on the skin they vibrate and wobble during movement tasks, creating artefacts that must be removed using low-pass filtering with low cut-off frequencies. These limitations do not indicate that the results from prior investigations using skin mounted markers and different marker and force filtering cut-off frequencies are devoid of any value. Hewett *et al*⁶ prospectively screened young female athletes and identified peak KAM measured during a drop vertical jump task as the most significant predictor of future ACL injury. Marker and force data collected during their investigation were low-pass filtered using different cut-off frequencies (9 and 50 Hz, respectively), and they reported that peak KAM was the most important predictor of ACL injury risk even after minimising the influence of any potential artefacts or trial-to-trial variability by averaging peak KAM of three trials per subject in a large prospective cohort.

The precise KAM threshold that delineates future ACL injury risk may be debatable, but it is paramount that we use the most sensitive measures available to identify athletes who may be at risk of future ACL injury. Using excessively low cut-off frequencies to filter marker and force data may obscure physiologically meaningful information, and lead to artificially small KAM values and costly false-negative findings. The current results indicate that prior reports of ACL prediction using the peak KAM are likely representative of important joint loads that predict injury risk. Future work is warranted to determine the potential to predict injury risk using alternative filtering techniques.

The purpose of this study was to evaluate the effect of aggressive low-pass filtering cut-off frequency on the peak KAM computed during a DVJ, with particular implications on ACL injury risk. We reported the relevant effects of cut-off frequency on peak KAM; however, a prospective cohort study would be able to evaluate the ability of peak KAM calculated using matched cut-off frequencies to predict ACL injury risk. We reported changes in peak KAM

due to selecting either the same low cut-off frequency or different cut-off frequencies; however, we were unable to determine to what extent the decrease in peak KAM reported when the same low cut-off frequencies were used was solely due to attenuation of the GRF signal.

Acknowledgments

We would like to thank Sam Wordeman, Stephanie Di Stasi, Mike McNally and the Biodynamics Laboratory research teams at both Ohio State University and Cincinnati Children's Hospital for assistance with data collection.

Funding National Institutes of Health.

REFERENCES

1. Arendt E, Agel J, Dick R. Anterior cruciate ligament injury patterns among collegiate men and women. *J Athl Train*. 1999; 34:86–92. [PubMed: 16558564]
2. Englund M, Roos H, Lohmander LS. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum*. 2004; 50:3145–52. [PubMed: 15476248]
3. Ardern CL, Webster KE, Taylor NF, et al. Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery: two-thirds of patients have not returned by 12 months after surgery. *Am J Sports Med*. 2011; 39:538–43. [PubMed: 21098818]
4. Paterno MV, Rauh MJ, Schmitt LC, et al. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sport Med*. 2012; 22:116–21. [PubMed: 22343967]
5. Myer GD, Ford KR, Paterno MV, et al. The effects of generalized joint laxity on risk of anterior cruciate ligament injury in young female athletes. *Am J Sports Med*. 2008; 36:1073–80. [PubMed: 18326833]
6. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med*. 2005; 33:492–501. [PubMed: 15722287]
7. Myer GD, Ford KR, Foss KDB, et al. The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. *Clin J Sport Med*. 2009; 19:3–8. [PubMed: 19124976]
8. Zebis MK, Andersen LL, Bencke J, et al. Identification of athletes at future risk of anterior cruciate ligament ruptures by neuromuscular screening. *Am J Sports Med*. 2009; 37:1967–73. [PubMed: 19574475]
9. Hewett TE, Zazulak BT, Myer GD. Effects of the menstrual cycle on anterior cruciate ligament injury risk: a systematic review. *Am J Sports Med*. 2007; 35:659–68. [PubMed: 17293469]
10. Hewett TE, Lynch TR, Myer GD, et al. Multiple risk factors related to familial predisposition to anterior cruciate ligament injury: fraternal twin sisters with anterior cruciate ligament ruptures. *Br J Sports Med*. 2010; 44:848–55. [PubMed: 19158132]
11. Hewett TE, Lindenfeld TN, Riccobene JV, et al. The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *Am J Sports Med*. 1999; 27:699–706. [PubMed: 10569353]
12. Padua, DA.; Marshall, SW.; Beutler, AI., et al. Prospective Cohort Study of Biomechanical Risk Factors of ACL Injury: the JUMP-ACL Study; American Orthopaedic Society of Sports Medicine Annual Meeting; 2009.
13. Bisseling RW, Hof AL. Handling of impact forces in inverse dynamics. *J Biomech*. 2006; 39:2438–44. [PubMed: 16209869]
14. Kristianslund E, Krosshaug T, van den Bogert AJ. Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention. *J Biomech*. 2012; 45:666–71. [PubMed: 22227316]

15. Hewett TE, Myer GD, Roewer BD, et al. Letter to the editor regarding 'Effect of low pass filtering on joint moments from inverse dynamics implications for injury prevention'. *J Biomech.* 2012; 45:1–2. [PubMed: 22112919]
16. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc.* 2003; 35:1745–50. [PubMed: 14523314]
17. Bell L, Pedersen R, Brand A. A comparison of the accuracy of several hip center location prediction methods. *J Biomech.* 1989; 23:617–21. [PubMed: 2341423]
18. Myer GD, Ford KR, Khoury J, et al. Biomechanics laboratory-based prediction algorithm to identify female athletes with high knee loads that increase risk of ACL injury. *Br J Sports Med.* 2010; 45:245–52. [PubMed: 20558526]
19. Genuario JW, Faucett SC, Boublik M, et al. A cost-effectiveness analysis comparing 3 anterior cruciate ligament graft types: bone-patellar tendon-bone autograft, hamstring autograft, and allograft. *Am J Sports Med.* 2012; 40:307–14. [PubMed: 22085728]
20. Winter, DA. *Biomechanics and motor control of human movement.* 3rd edn.. Hoboken: John Wiley & Sons Inc; 2005.
21. Ford KR, Myer GD, Hewett TE. Reliability of landing 3D motion analysis: implications for longitudinal analyses. *Med Sci Sports Exerc.* 2007; 39:2021–8. [PubMed: 17986911]
22. Ford KR, Myer GD, Toms HE, et al. Gender differences in the kinematics of unanticipated cutting in young athletes. *Med Sci Sports Exerc.* 2005; 37:124–9. [PubMed: 15632678]
23. Collins JJ, Whittle MW. Impulsive forces during walking and their clinical implications. *Clin Biomech.* 1989; 4:179–87.

What this study adds

This work provides information that may help clinicians interpret the findings reported in biomechanical research studies.

Figure 1.

The average external knee abduction moment (KAM) during the drop vertical jump for each filtering cut-off frequency condition. Time-normalised data for the first 50% of stance are presented to clarify the effect of cut-off frequency condition on KAM near initial contact. Peak KAM was significantly larger under all conditions in which marker and force data were filtered using different marker and ground reaction force cut-off frequencies.

Figure 2.

The averaged external knee abduction moment for two subjects produced using the same low cut-off frequency (solid line) and different cut-off frequencies (dashed line). The effect of applying different cut-off frequencies to marker and ground reaction force data was negligible for subject A and large for subject B.

Subject	Peak Knee Abduction Moment (N*m)					
	Low-pass filtering cut-off frequency (marker, force)					
	(10, 50)	(12, 50)	(15, 50)	(10,10)	(12, 12)	(15, 15)
8d	-61.92	-62.01	-62.07	-61.94	-62.06	-62.12
14d	-52.80	-43.37	-39.70	-42.58	-35.69	-35.86
21n	-49.81	-49.96	-50.10	-49.57	-49.88	-50.37
15n	-44.15	-43.81	-43.23	-38.04	-38.63	-39.13
8n	-41.39	-41.30	-40.96	-36.52	-36.63	-36.73
17d	-41.07	-41.37	-42.77	-35.89	-36.13	-38.96
24d	-40.38	-39.94	-39.16	-16.19	-16.77	-17.80
11d	-39.06	-38.61	-37.71	-17.37	-18.34	-19.43
22d	-38.89	-39.32	-39.82	-40.12	-40.36	-40.52
6n	-38.52	-38.22	-38.01	-37.07	-37.02	-37.14
5d	-37.82	-37.50	-37.02	-37.00	-36.97	-36.95
24n	-37.47	-38.86	-40.89	-13.95	-15.80	-18.19
4n	-37.04	-36.00	-34.75	-27.91	-28.84	-29.83
13n	-36.84	-37.38	-37.69	-19.62	-21.14	-22.19
12d	-36.78	-35.28	-33.38	-25.16	-25.54	-25.93
20d	-36.11	-37.86	-40.29	-33.56	-34.75	-38.61
12n	-35.92	-35.21	-35.47	-27.75	-28.73	-29.75
17n	-35.90	-35.86	-35.84	-13.98	-15.29	-19.02
6d	-35.84	-35.17	-33.85	-25.45	-25.74	-26.15
23d	-34.08	-34.28	-34.55	-31.51	-32.17	-32.93
21d	-34.03	-34.21	-34.29	-16.36	-16.46	-16.55
9d	-33.01	-32.43	-31.23	-15.59	-16.32	-17.63
9n	-31.21	-32.09	-33.32	-31.85	-32.52	-33.01
5n	-29.93	-30.00	-30.06	-29.12	-29.07	-29.21
14n	-29.78	-29.96	-29.93	-25.83	-26.09	-27.46
4d	-27.39	-27.12	-26.75	-23.22	-23.43	-23.87
13d	-27.16	-27.42	-27.79	-20.56	-21.42	-22.67
23n	-25.04	-25.80	-26.33	-13.70	-14.27	-15.40
15d	-24.90	-24.46	-23.82	-17.35	-17.94	-18.42
19d	-24.46	-23.38	-22.43	-20.60	-21.25	-21.91
20n	-23.31	-24.66	-25.90	-23.18	-24.13	-25.07
22n	-23.26	-22.75	-22.27	-8.39	-10.99	-15.09
7d	-22.66	-23.10	-23.37	-20.98	-21.39	-21.78
18d	-22.49	-22.42	-22.77	-16.81	-17.87	-19.86
10d	-21.45	-21.01	-20.76	-18.99	-19.63	-20.34
11n	-20.83	-21.26	-21.74	-17.88	-19.11	-20.32
18n	-19.14	-19.04	-18.81	-17.45	-17.73	-18.08
3d	-18.82	-19.05	-19.16	-18.95	-18.97	-19.03
3n	-18.48	-18.87	-19.13	-8.06	-8.72	-9.54
19n	-18.22	-18.72	-19.56	-13.09	-13.52	-14.32
7n	-16.10	-16.15	-16.44	-12.78	-12.96	-13.84
2n	-16.09	-16.73	-17.71	-12.77	-13.66	-15.37
2d	-15.33	-16.83	-19.27	-14.48	-16.56	-18.95
10n	-14.67	-14.52	-14.57	-5.48	-6.33	-8.14

Figure 3.

The average peak external knee abduction moment (KAM) for the dominant (d) and non-dominant limbs (n) of the 22 subjects included in the analysis. Data are ranked from largest (darkest shade) to smallest (lightest shade) peak KAM with marker and ground reaction forces data filtered at 10 and 50 Hz, respectively, because peak KAM has been reported as a sensitive predictor of anterior cruciate ligament injury risk using these filtering conditions.⁶ Seventeen of the 22 subjects had peak KAM values exceeding 25.25 Nm when marker and force data were filtered using different cut-off frequencies. Three of those 17 subjects did

not have peak KAM values exceeding 25.25 when data were filtered using the same low cut-off frequencies.

Table 1
The mean peak external knee abduction moment (KAM) during the drop vertical jump is presented for each marker and force low-pass filtering cut-off frequency combination

Cut-off frequency (marker, force) (Hz)	Peak KAM (Nm) Mean (SD)	95% CI
10, 10	-23.97 (11.7)	(-27.4 to -20.5)
12, 12	-24.47 (11.3)	(-27.8 to -21.1)
15, 15	-25.53 (11.0)	(-28.8 to -22.3)
10, 50	-31.13 (10.7)	(-34.3 to -28.0)
12, 50	-30.98 (10.2)	(-34.0 to -28.0)
15, 50	-31.01 (10.1)	(-34.0 to -28.0)