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Effect of low pass filtering on joint moments from inverse dynamics: Implications for injury prevention

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Abstract

Analyses of joint moments are important in the study of human motion, and are crucial for our understanding of e.g. how and why ACL injuries occur. Such analyses may be affected by artifacts due to inconsistencies in the equations of motion when force and movement data are filtered with different cut-off frequencies. The purpose of this study was to quantify the effect of these artifacts, and compare joint moments calculated with the same or different cut-off frequency for the filtering of force and movement data. 123 elite handball players performed sidestep cutting while the movement was recorded by eight 240 Hz cameras and the ground reaction forces were recorded by a 960 Hz force plate. Knee and hip joint moments were calculated through inverse dynamics, with four different combinations of cut-off frequencies for signal filtering: movement 10 Hz, force 10 Hz, (10-10); movement 15 Hz, force 15 Hz; movement 10 Hz, force 50 Hz (10-50); movement 15 Hz, force 50 Hz. The results revealed significant differences, especially between conditions with different filtering of force and movement. Mean (SD) peak knee abduction moment for the 10-10 and 10-50 condition were 1.27 (0.53) and 1.64 (0.68) Nm/kg, respectively. Ranking of players based on knee abduction moments were affected by filtering condition. Out of 20 players with peak knee abduction moment higher than mean+1SD with the 10-50 condition, only 11 were still above mean+1SD when the 10-10 condition was applied. Hip moments were very sensitive to filtering cut-off. Mean (SD) peak hip flexion moment was 3.64 (0.75) and 5.92 (1.80) under the 10-10 and 10-50 conditions, respectively. Based on these findings, force and movement data should be processed with the same filter. Conclusions from previous inverse dynamics studies, where this was not the case, should be treated with caution.

Introduction

Analyses of joint moments are important in the study of human motion, as joint moments correspond to resultant muscle forces and loading of passive structures. The joint moments are usually calculated using inverse dynamics on force plate recordings and marker position data from infrared camera systems. There is a need to low-pass filter position data to remove random noise, especially because errors are amplified when differentiating position data for calculating segment inertia for inverse dynamics (Chiari et al., 2005). Position data is typically filtered with 5-20 Hz cut-off frequency, based on the frequency content of normal movement and of the errors. Force platform data, on the other hand, is considered accurate and with less need of filtering, as force data is not differentiated in the inverse dynamics procedure (Davis et al., 1991; Chappell et al., 2002; Hewett et al., 2005; Sigward and Powers, 2007; Pollard et al., 2010). However, concern has been raised for possible artifacts when using different cut-off frequency for force and position data in inverse dynamics, especially for high-impact movements (van den Bogert and de Koning, 1996; Bisseling and Hof, 2006), typically analyzed in performance and sports injury biomechanics.

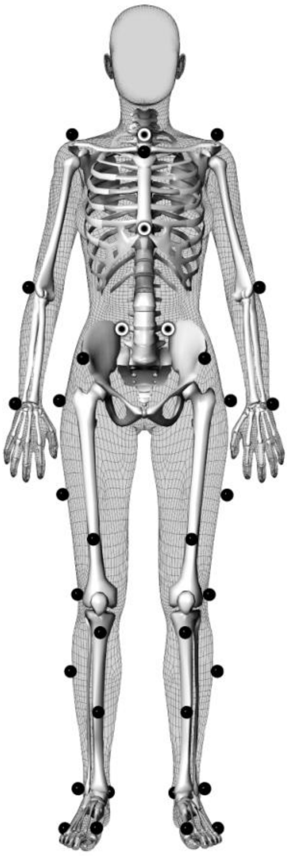
With high-intensity movements like running and jumping, peaks in ground reaction forces and segment accelerations are seen shortly after ground contact (Bisseling and Hof, 2006). With a high cut-off frequency for force and a low cut-off frequency for movement data, impact peaks are retained only in external forces, but not in segment accelerations. This inconsistency within the equations of motion will give rise to artifacts in the joint moment curves, as the acceleration of the segments will not correspond to the measured ground reaction force (van den Bogert and de Koning, 1996; Bisseling and Hof, 2006). This can be exemplified by an analysis of knee moments in jumping. A study on drop jumps from 30 cm analyzed using accelerometers found the peak tibial acceleration to be 15.8 g (Moran and Marshall, 2006). The shank mass of 3.7 kg (Zatsiorsky and Seluyanov, 1983), decelerated at 15.8 g represents an inertial force term 573 N in the inverse dynamic equation for the shank. The associated load can be captured by the force plate measuring ground reaction forces, but the acceleration peak is so short that will be removed by the cut-off frequency necessary to obtain noise-free movement data from optical data (Bisseling and Hof, 2006). Assuming a distance from knee joint to shank center of mass of 0.24 m (Zatsiorsky and Seluyanov, 1983), the resulting error in knee moment could be as large as 573 N x 0.24 m = 138 Nm. Higher filter frequencies are no option because the result will be too noisy due to inherent limitations in marker-based systems (Bisseling and Hof, 2006). The combination of data filtered with different cut-off frequency in inverse dynamics calculations generate artifacts that stem from the inability to measure segment accelerations. The calculation of hip moments is likely to be the most affected, as it depends on the acceleration of foot, shank and thigh segments.

Impact artifacts due to different filtering of force and movement may have affected the results of a range of biomechanic experiments, e.g. studies of sprint running (Bezodis et al., 2008; Hunter et al., 2004; Johnson and Buckley, 2001), ACL injury risk (Hewett et al., 2005), sidestep cutting mechanics (Sigward and Powers, 2007; Pollard et al., 2010) and jumping mechanics (Chappell et al., 2002). These studies have included both knee and hip joint moments. Artifacts may be interpreted as actual joint moments, and both the magnitude of the joint moments and the ranking of players based on these measures may be affected. The real difference in results between different choices of cut-off frequency is not known, and can have major implications for the interpretation of results. The main purpose of this study was to quantify the effect of choice of cut-off frequencies on the joint moments typically calculated in inverse dynamics analysis of side step cutting motion. We specifically wanted to investigate the cut-off frequencies typically used in previous studies. Secondly, we wanted to assess whether filtering condition affected the ranking of players based on their maximal knee abduction moments, as this is a factor used for injury prediction (Hewett et al., 2005).

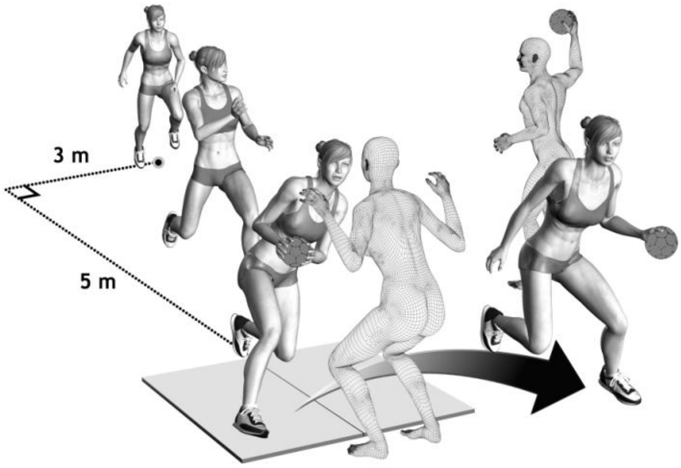
Methods

All Division I players in the Norwegian female handball league were invited to baseline testing for a cohort study initiated to investigate risk factors for ACL injuries, and the 125 tested back and wing players were selected for analysis. All players were match fit at the time of testing, but two were excluded due to technical problems. The final sample consisted of 123 players (22.5±7.0 years, 171±7 cm, 67±7 kg, mean±SD). The study was approved by the Regional Ethics Committee and informed consent was obtained from all players.

The players performed sidestep cutting in a biomechanics lab. Eight 240 Hz infrared cameras (ProReflex, Qualisys, Gothenburg, Sweden) recorded the movement of 35 reflective markers attached over anatomical landmarks (Figure 1). Ground reaction force and center of pressure were recorded by a force platform collecting at 960 Hz (AMTI, Watertown, Massachusetts, USA). The players cut past a human static defender (170 cm), starting five meters in front of the defender and arriving at an angle of approximately 30° on the long axis of the runway. They were instructed to perform cuts similar to what they would do during active game play, focusing on faking the defender to go to one side and passing her on the other side. The defender adjusted her position between trials to ensure that the player stepped onto the force platform with her stance foot. The players were allowed up to three practice cuts to familiarize themselves with the situation, and at least six successful trials from each side (left-right and right-left) were completed. Qualified personnel ensured that these trials were performed with match-like intensity with the stance foot on the force platform and all markers firmly attached to the player's skin. Prior to sidestep cutting a static calibration trial was performed to determine the anatomical coordinate systems.



Figur 1: Marker setup.



Figur 2: Testing situation. Players started at an angle of approximately 33° on the long axis of the runway. They were instructed to try to fake the defender into going to one side while cutting to the other. The defender was completely static and adjusted her position between the trials so the players hit the force platforms with their normal sidestep cutting technique

One right-left sidestep cut was selected for analysis. The motion analysis system was calibrated according to guidelines of the manufacturer, and marker trajectories were calculated and tracked with the Qualisys Track Manager (Qualisys, Gothenburg, Sweden). The kinetics and kinematics were calculated in custom Matlab scripts (MathWorks Inc., Natick, MA, USA).

The contact phase was defined as the period where the unfiltered vertical ground reaction force exceeded 20 N. Marker trajectories and force data were filtered and interpolated using Woltring's smoothing spline in the cubic mode (Woltring, 1986). If one of the four pelvic markers were missing for more than 20 frames, it was interpolated based on the position of the remaining three pelvic markers. Different combinations of cut-off frequencies for force and marker data were selected for the analysis, as described in 'Statistical treatment'.

The hip joint center was calculated using the method proposed by Bell et al, with the anterior-posterior position of the hip joint decided by the anterior-posterior position of the marker over the greater trochanter (Bell et al., 1990). The knee joint center was defined according to the work of Davis (1991), and the ankle joint center according to Eng and Winter (1995). Anatomical coordinate systems of the thigh and shank were determined from the static calibration trial. The vertical axis was defined in the direction from distal to proximal joint center, while the anterio-posterior axis was defined perpendicular to the vertical axis with no mediolateral component. The third axis was the cross product of the vertical and antero-posterior axis. Consequently, all segments had neutral internal/external rotation in the static calibration trial. Technical, dynamic thigh and shank segment coordinate systems were found using an optimization procedure involving singular value decomposition (Soderkvist and Wedin, 1993).

Inertia parameters were estimated based on 46 measures of segment heights, perimeters and widths using a modified Yeadon's method (Yeadon, 1990), with hand and foot parameters calculated with the method of Zatsiorsky (1983). Hip and knee joint moments were calculated with inverse dynamics using recursive Newton-Euler equations of motion as described by Davis et al. (1991) and projected onto the three rotational axes of the joint according to the joint coordinate system standard (Bresler and Frankel, 1950; Wu et al., 2002; Grood and Suntay, 1983).

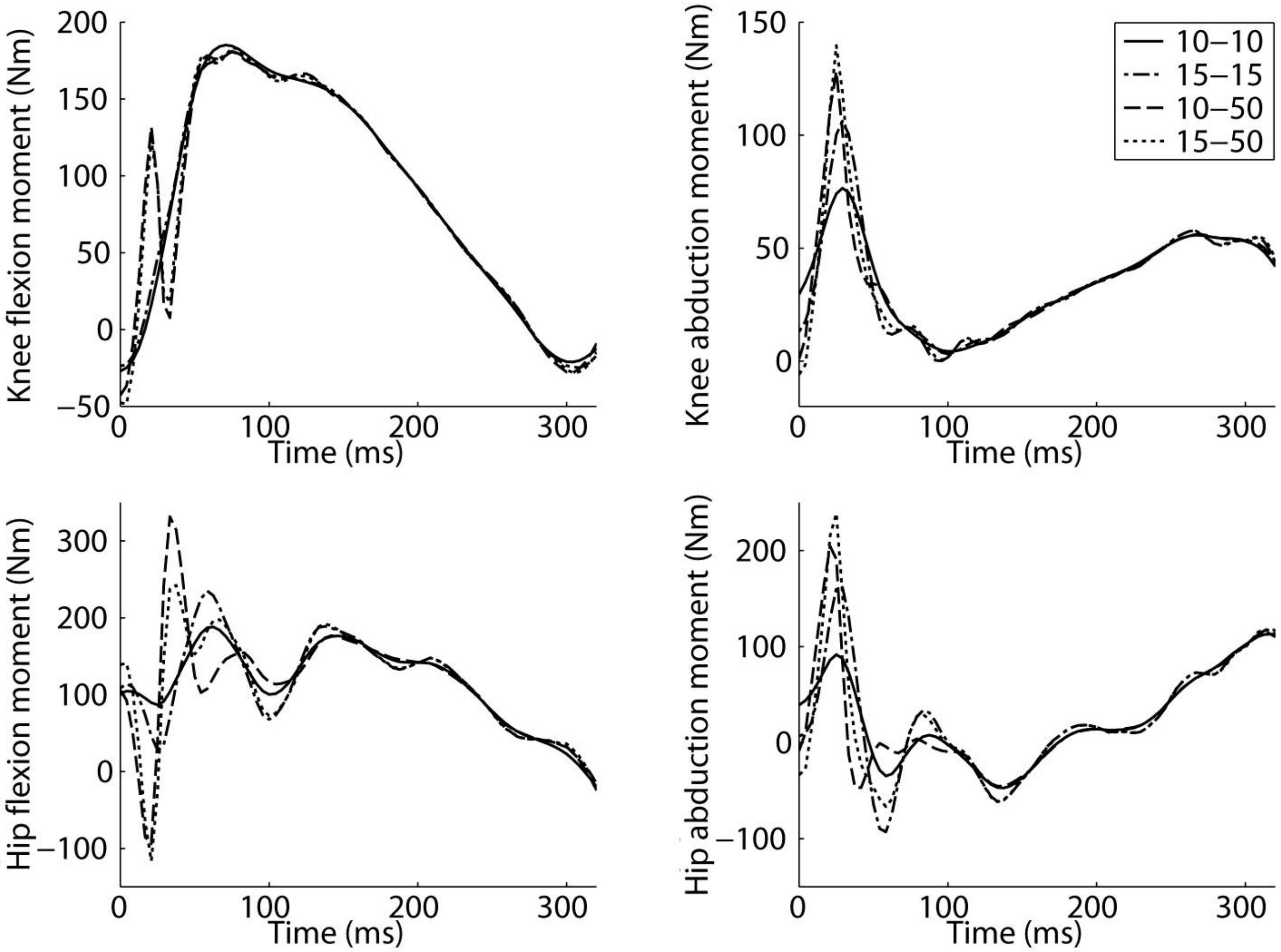
Joint moments were calculated under four different filtering conditions, varying the cut-off frequency for the Woltring smoothing spline. The cut-off frequencies were selected from what has been commonly used in previous studies. The four conditions were: both movement and force filtered with 10 Hz cut-off ('10-10'); both movement and force filtered with 15 Hz cut-off ('15-15'); movement filtered with 10 Hz cut-off, force with 50 Hz cut-off ('10-50'); movement filtered with 15 Hz cut-off, force with 50 Hz cut-off ('15-50').

Statistical treatment

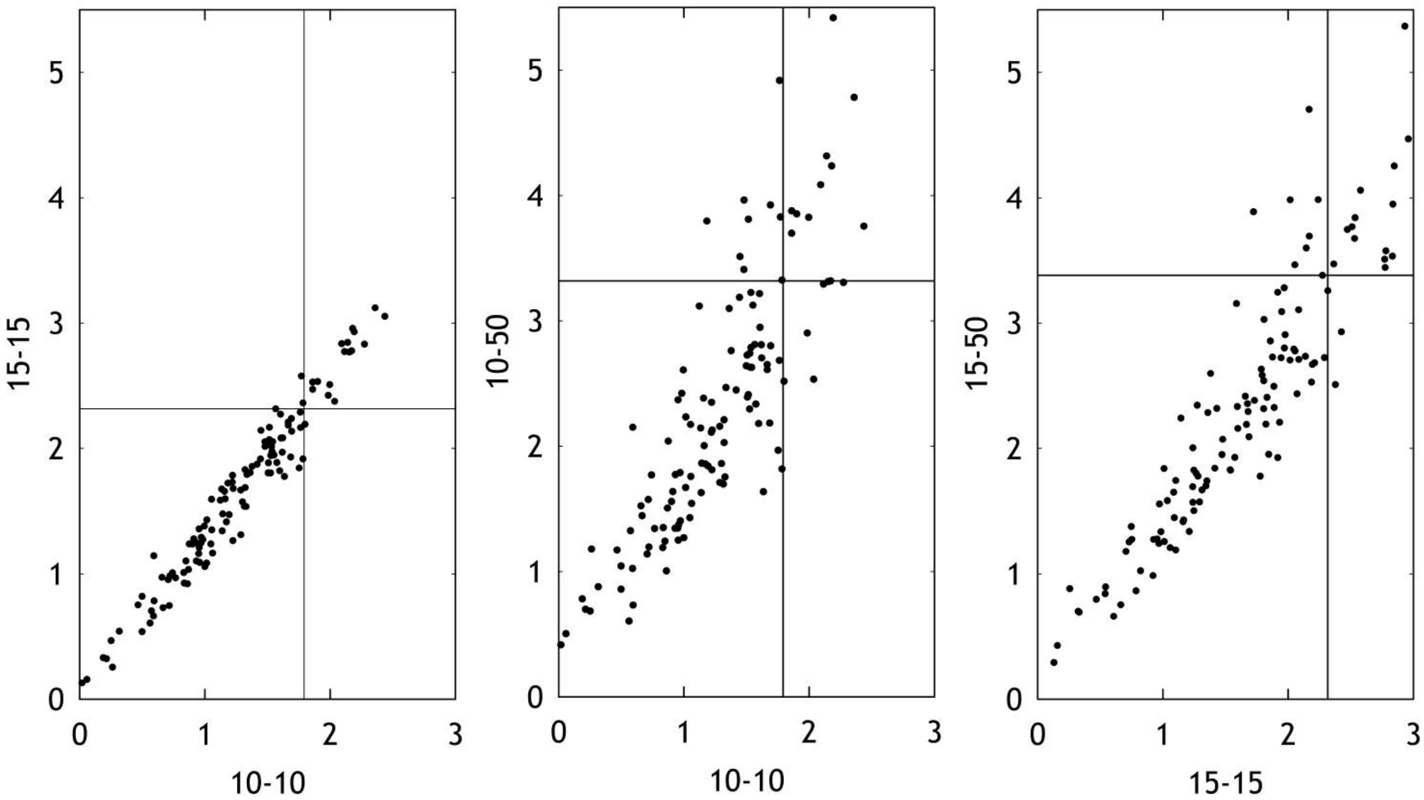
Statistical analysis was performed in SPSS 18 (SPSS Inc., Chicago, IL, USA). An alpha value of 0.05 was used for the hypothesis testing, with a Bonferroni correction for repeated t-tests. We chose to analyze the first 100 ms of stance as this is when accelerations are highest and thereby artifacts most likely to occur (Bisseling and Hof, 2006; van den Bogert and de Koning, 1996; Moran and Marshall, 2006). This is also when valgus moments are found to be maximal (McLean et al., 2005). Maximum knee flexion moment, knee abduction moment, hip flexion moment and hip abduction moment first 100 ms of stance phase were compared across the four filtering conditions in a repeated-measures ANOVA. Three post-hoc paired t-tests were performed for each ANOVA in case of significant differences across conditions. Conditions compared were 10-10 and 15-15; 10-10 and 10-50 and 15-15 and 15-50. To display maximum differences between conditions, 95% confidence intervals for the maximum absolute difference in knee flexion moment, knee abduction moment, hip flexion moment and hip abduction moment during the first 100 ms was found for 10-10 vs. 15-15, 10-10 vs. 10-50 and 15-15 vs. 15-50. To assess whether filtering condition affected the ranking of players, Spearman's ρ was calculated for the maximum knee abduction moment during the first 100 ms between the 10-10 and the 15-15 conditions; the 10-10 and the 10-50 conditions and the 15-15 and the 15-50 conditions (Altman, 1991).

Results

We observed a sudden spike in the joint moments at approximately 50 ms (figure 3). There was a significant difference in maximum values between all conditions (Table 1 and 2), as well as for maximum absolute differences between conditions first 100 ms (table 3). Spearman’s rank correlation for maximum knee abduction moment was lower for the comparison of 10-50 vs 10-10 and 15-50 vs. 15-15, compared to the 10-10 vs. 15-15 (Table 4), indicating that the ranking of players based on maximum knee abduction moment was affected by filtering with different cut-off frequencies for force and movement. We indicated a cut-off of one standard deviation above the mean for knee abduction moments to illustrate the effect of filtering condition on the classification of players. Of the 20 players above the cut-off with the 10-50 condition, only 11 would still be considered high-risk when applying the 10-10 condition. The grouping was more consistent when an identical cut-off frequency was used for both force and movement signals. 16 out of 18 players above the cut-off under the 15-15 condition were still above cut-off under the 10-10 condition (Figure 4). Maximum vertical ground reaction force was 26.2, 29.8 and 35.6 N/BW for 10, 15 and 50 Hz cut-off frequency for force filtering.



Figur 3: External joint moments (Nm) for a typical player with different combinations of cut-off frequencies for the filtering of force and movement data. A-B: A and B refer to cut-off frequency for marker and force data respectively.



Figur 4: Relationship between knee abduction moments (Nm/kg) from different combinations of cut-off frequencies for the filtering of force and movement data. N = 123. Lines at mean+1SD. A-B: A and B refer to cut-off frequency for marker and force data respectively

Table 1: Repeated measures ANOVA for peak external joint moments (Nm/kg) first 100 ms between different combinations of cut-off frequencies for the filtering of force and movement data. N = 123. 10-10: 10 Hz cut-off frequency for marker data and 10 Hz cut-off frequency for force data.

	10-10	15-15	10-50	15-50	
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	p-value
Knee flexion moment	3.24 (0.63)	3.21 (0.64)	3.27 (0.63)	3.30 (0.65)	<0.001
Knee abduction moment	1.27 (0.53)	1.64 (0.68)	2.30 (1.02)	2.34 (1.04)	<0.001
Hip flexion moment	3.64 (0.75)	4.51 (0.99)	5.92 (1.80)	5.18 (1.21)	<0.001
Hip abduction moment	1.30 (0.61)	2.16 (0.95)	3.57 (1.62)	3.81 (1.81)	<0.001

Table 2: Paired t-tests of difference in peak external joint moments (Nm/kg) first 100 ms between different combinations of cut-off frequencies for the filtering of force and movement data. N = 123. Corrected p-value. 10-10: 10 Hz cut-off frequency for marker data and 10 Hz cut-off frequency for force data.

	10-10 vs. 15-15		
	Mean	95% CI	p-value
Knee flexion moment	-0.03	(-0.01,-0.04)	0.009
Knee abduction moment	0.37	(0.33,0.40)	<0.001
Hip flexion moment	0.87	(0.80,0,94)	<0.001
Hip abduction moment	0.86	(0.77,0.95)	<0.001

	10-10 vs. 10-50		
	Mean	95% CI	p-value
Knee flexion moment	0.04	(0.00,0,07)	0.235
Knee abduction moment	1.03	(0.91,1.14)	<0.001
Hip flexion moment	2.27	(2.00,2.54)	<0.001
Hip abduction moment	0.66	(0.52,0.81)	<0.001

	15-15 vs. 15-50		
	Mean	95% CI	p-value
Knee flexion moment	0.09	(0.05,0,12)	<0.001
Knee abduction moment	0.70	(0.61,0.79)	<0.001
Hip flexion moment	0.67	(0.52,0.81)	<0.001
Hip abduction moment	1.65	(1.45,1.85)	<0.001

Table 3: Maximum absolute differences in external joint moments (Nm/kg) first 100 ms between different combinations of cut-off frequencies for the filtering of force and movement data. N = 123. 10-10: 10 Hz cut-off frequency for marker data and 10 Hz cut-off frequency for force data.

	10-10 vs. 15-15		10-10 vs. 10-50		15-15 vs. 15-50	
	Mean	95% CI	Mean	95% CI	Mean	95% CI
Knee flexion moment	0.32	(0.30,0.34)	1.73	(1.62,1.84)	1.39	(1.29,1.48)
Knee abduction moment	0.40	(0.36,0.43)	1.21	(1.09,1.33)	0.93	(0.83,1.04)
Hip flexion moment	1.14	(1.06,1.21)	3.74	(3.47,4.00)	2.78	(2.58,2.99)
Hip abduction moment	1.02	(0.94,1.10)	2.50	(2.27,2.73)	1.96	(1.77,2.16)

Table 4: Spearman's ρ for correlation of ranking of players based on knee abduction moment different combinations of cut-off frequencies for the filtering of force and movement data. N = 123.

	ρ	95% CI
10-10 vs. 15-15	0.969	(0.946,0.979)
10-10 vs. 10-50	0.857	(0.785,0.905)
15-15 vs. 15-50	0.931	(0.890,0.955)

Discussion

There was a significant effect of filtering condition on joint moments, especially when comparing conditions with the same cut-off frequency for force and movement with conditions where there was a difference in the cut-off frequency selected for force and movement. The differences between conditions occur only in the impact phase, as is evident from figure 2. Maximum absolute difference between conditions is also markedly higher than the difference between peak values. The errors must be due to some systematic differences between conditions because differences arise early in the contact phase and seem independent of the magnitude of the joint moment. These artifacts are likely due to an inconsistency between impact peaks in the ground reaction force data and the lack of high-frequency components of segment accelerations (van den Bogert and de Koning, 1996). The problem is previously addressed by Bisseling and Hof (2006), but this is the first study to quantify the effects of the artifacts in a large sample and in both the sagittal and frontal planes.

Different cut-off frequency for filtering of force and movement in inverse dynamics analyses is widely used despite the resulting artifacts in joint moment curves (Johnson and Buckley, 2001; Chappell et al., 2002; Hewett et al., 2005; Sigward and Powers, 2007; Pollard et al., 2010; Hunter et al., 2004; Bezodis et al., 2008). The differences we found between the methods affect the interpretation of previous results. Considering joint angles or ground reaction forces on their own will not be affected by these artifacts, although they will depend on the choice of cut-off frequency for filtering.

The difference in knee abduction moment measures between filtering methods challenges the validity of the results from previous studies related to anterior cruciate ligament (ACL) injuries. Not only is the magnitude of the knee abduction moment different between the methods, the ranking of players based on this measure is also affected by whether the force and movement are filtered with the same filtering frequencies. The difference in ranking of players between methods will affect any study that compares knee abduction moments between groups or correlate knee abduction moments to other variables like injuries or kinematic factors.

Important studies of ACL injury risk, sidestep cutting and jumping are affected by possible artifacts in knee abduction moments. Hewett et al. found a relation between knee abduction angles and moments in drop jumps and ACL injury in a prospective cohort study (Hewett et al., 2005). This study is at least partly responsible for the focus on knee abduction in ACL injury research. However, as can be seen from our results the different filtering of force and movement can lead to considerable errors in joint moments, making them less reliable. Sigward and Powers investigated the difference in sidestep cutting technique between players with high or normal knee abduction moments (Sigward and Powers, 2007). Their grouping of their players would have been significantly different if the same cut-off frequency had been applied for force and movement data. Similarly, correlations between kinematic measures and knee abduction moments are affected by filtering condition (Pollard et al., 2010). Chappell et al. calculated joint contact forces in stop-jumps to investigate possible ACL injury mechanisms (Chappell et al., 2002). The calculation of these contact forces rely on the accelerations of segments, and are likely to yield impact artifacts with different filtering of force and movement. These unphysiological artifacts may be what the authors interpreted as anterior shear forces in support of the quadriceps drawer mechanism of ACL injury. This injury mechanism seems less likely if the reported anterior shear forces are artifacts due to inconsistency between force and movement peaks in the early contact phase.

Calculation of hip moments seems to be very sensitive to filtering method. The effect of different filtering frequency for force and movement is substantial, but there are also important differences between filtering with a 10 or 15 Hz cut-off frequency. Hip moments are more sensitive to the effect of segment accelerations than knee or ankle moments, as the acceleration of the foot, shank and thigh segments are taken into account when calculating hip joint moments (Davis et al., 1991). van den Bogert and de Koning discussed the need for different cut-off frequencies for inverse dynamics of different lower extremity joints (van den Bogert and de Koning, 1996). It seems clear that caution is needed when interpreting hip joint moments.

Analyses of sprint running have found impact peaks in knee and hip flexion moments that have been challenging to interpret (Hunter et al., 2004; Johnson and Buckley, 2001; Bezodis et al., 2008). These impact peaks have sometimes been interpreted as muscle actions, but they are probably unphysiological impact artifacts due to different filtering of force and movement (Bezodis et al., 2011).

Analysis of impact in motion analysis seems to be limited by the need to low-pass filter the data from reflective markers. As filtering of both force and movement is needed, the high-frequency content of sporting movements cannot be reliably analyzed, and this put a limit on the accuracy of inverse dynamics. Bisseling et al. tried to overcome these obstacles by measuring the acceleration of the segments directly, but were not able to calculate satisfactory results using accelerometers (Bisseling and Hof, 2006).

The difference between joint moments under different filtering conditions has been calculated for one movement only. The movement analyzed is widely used for motion analysis related to ACL injury, and is a typical movement in many sports (Benjaminse et al., 2011). There is no reason to believe that the artifacts found in this study are specific for sidestep cutting, as high-impact accelerations are also found in other movements such as drop jumps and running (Moran and Marshall, 2006; Hunter et al., 2004).

This study exposes the importance of considering cut-off frequencies for inverse dynamics. We found major differences between filtering conditions. Clear impact artifacts are found when different cut-off frequencies are used for force and movement data. Cut-off frequency for both force and movement data should be chosen after the cut-off frequency required from the marker data. New analyses or new research is needed to feel confident on previous results and earlier conclusions may have to be rethought. More research is needed on the nature of the peaks that are so evident in the joint moment curves when force and movement are filtered with different cut-off frequencies. To feel confident on the validity of results and be able to compare studies a consensus on how to perform low-pass filtering of motion analysis data is needed.

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Conflict of interest statement

No author has any financial and personal relationships with other people or organisations that could inappropriately influence their work.

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