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Can two-dimensional measured peak sagittal plane excursions during drop vertical jumps help identify three-dimensional measured joint moments?

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ABSTRACT

Background: Less optimal sagittal plane movement patterns are believed to increase knee injury risk in female athletes. To facilitate clinical screening with a user-friendly method, the purpose of the present study was to examine the temporal relationships between two-dimensional measured sagittal plane kinematics and three-dimensional joint moments during the double-leg drop vertical jump (DVJ) and single-leg DVJ (SLDVJ).

Methods: Fifty injury-free female athletes were tested. Maximal excursions of hip flexion, knee flexion and ankle dorsiflexion were measured through two-dimensional video analysis. Three-dimensional motion and ground reaction forces were recorded to calculate external hip flexion, knee flexion and knee abduction moments during the entire stance phase of DVJ and SLDVJ. One-dimensional statistical parametric mapping was used to examine relationships between peak two-dimensional kinematic variables and three-dimensional moment profiles.

Results: Hip flexion was significantly related to the hip and knee flexion moment for both tests and knee abduction moment for DVJ during the time frames corresponding with highest three-dimensional moments, while knee flexion was significantly related to the hip flexion moment during these time frames. No significant relationships were found for ankle dorsiflexion with any of the joint moments.

Conclusions: Two-dimensional measured sagittal plane hip flexion angles at the deepest landing position were associated with peak joint moments of the hip and knee during DVJ and SLDVJ, while the amount of knee flexion was only associated with the hip flexion moment. Assessment of knee injury risk with two-dimensional video analysis could benefit from measuring maximal hip flexion, more so than knee flexion.

KEYWORDS

screening, female athletes, knee injury, two-dimensional video analysis

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1. Introduction

Acute and overuse knee injuries are common in sports involving jump-landing movements, especially in female athletes [1,2]. Whilst three-dimensional (3D) measurements are considered to be the gold standard in assessing complex movement patterns, two-dimensional (2D) video analysis may be a useful alternative to screen athletes in clinical practice [3-6]. Despite the increasing evidence that knee injuries may be caused by multi-planar mechanisms [7-9], and the suggestions to assess multi-segmental and multi-planar movement quality to identify those athletes with highest injury risk [8,10], most studies using 2D video analysis only focused on the frontal plane [3-6]. Only a limited number of studies [11,12] have performed sagittal plane movement analysis during athletic screening tests.

Landing with a more erect body position in the sagittal plane increases the vertical ground reaction forces [13], external knee abduction moment [14] and external knee flexion moment while the external hip flexion moment has been found to be decreased [15]. Although specific knee joint tissue loading cannot be directly derived from these biomechanical parameters, increased external knee flexion moments and associated increased quadriceps activation [13,16] were previously related to increased anterior tibial shear forces [17], patellofemoral joint reaction forces [18,19], and patellar tendon forces [20] which are believed to be important factors in the development of respectively anterior cruciate ligament injuries [21], patellofemoral pain [22] and patellar tendinopathy [23]. Increased knee abduction moments have prospectively been shown to predict patellofemoral pain [24] and anterior cruciate ligament injuries [25]. Therefore, this more erect landing strategy is believed to increase both acute and overuse knee injury risk [8,26,27].

To the best of our knowledge, there is no evidence showing the extent to which 2D measured sagittal plane kinematics are related to these 3D joint moments. The exploration of this relationship is a critical step to translate findings from laboratory settings to clinical practice.

The main goal of this study was therefore to examine the temporal relationships between 2D measured sagittal plane kinematics and 3D joint moments during the double-leg drop vertical (DVJ) and single-leg DVJ (SLDVJ). Both the DVJ [24,25,28] and SLDVJ [3,6] have been used previously to assess biomechanical dysfunctions in athletes. A part of this work was presented previously in an abstract form at the IOC World Conference Prevention of Injury & Illness in Sport, Monaco 2014 [29].

2. Materials and Methods

2.1 Participants

A total of 50 elite female athletes (22 soccer, 11 handball and 17 volleyball) were tested (mean $\pm$ SD: age = 21.3 ± 3.4 years; height = 1.72 ± 0.10 m; weight = 66.1 ± 8.5 kg). Athletes were recruited from one soccer, one handball and one volleyball team of the highest national competition level. Participants were injury and pain free, and above 16 years old. Appropriate ethical approval was granted by the local ethical committee prior to the commencement of the study. Before participating in the study, all participants read and signed the informed consent form.

2.2 Procedure and measurements

All participants wore a sports bra, tight-fitting shorts and standardized neutral indoor shoes (Kelme Indoor Copa). If necessary, long hair was tied up to avoid marker occlusion. Before the start of the tests, all participants executed a standardized warm-up program, consisting of a series of double-leg squats (2x8) and jumps (2x5) [6]. All participants completed the DVJ and SLDVJ. Participants were allowed to familiarize themselves with the tests by performing 3 practice repetitions before the start of the tests. The same researcher provided all specific instructions to each participant.

During the DVJ, participants were asked to drop off a box of 30 cm with two legs, with their feet positioned 20 cm apart at the beginning of the task, followed by a maximum vertical jump [28]. Participants were instructed to jump as high as possible by attempting to reach an overhead target at an unobtainable height of 300 cm with both hands. A trial was not valid if the participants jumped off the box instead of dropping, if they reached with only one hand, or if they clearly lost balance or fell during the test [25,28]. These criteria were visually judged by the examiner [28].

During the SLDVJ, participants were asked to drop off a box of 10 cm with one leg, followed by a maximum vertical jump on the same leg [3,6]. Participants were instructed to jump as high as possible by attempting to reach an overhead target at an unobtainable height of 300 cm with both hands. A trial was not valid if the participants jumped off the box instead of dropping, if the non-supporting leg touched the ground, if they reached with only one hand, or if they clearly lost balance or fell during the test [3,6]. These criteria were visually judged by the examiner [3,6].

The first three valid trials were selected based on the previously mentioned criteria and included for further analysis. Only the dominant side was analyzed for both the DVJ and SLDVJ. The dominant leg was defined as the preferred leg to kick a ball. The order of the tests was determined randomly. Afterwards, body height and weight were measured.

Each participant was instrumented with 44 spherical reflective markers positioned according to a 6-degrees-of-freedom eight segment 'Lower Limb and Trunk' model including feet, upper and lower legs, pelvis and trunk [28]. Segmental coordinate systems were defined as in the Liverpool John Moores University model [28], using separate trials for anatomical calibration [30] and for calculating functional hip joint centres [31] and functional knee joint axis [32]. The ankle joint centre was defined as the midpoint between both malleoli markers. All modelling and analyses were undertaken in Visual 3D (v.4.83, C-motion, Germantown, MD, USA) using geometric volumes to represent segments based on cadaver segmental data [33].

Force plate data were sampled at 1000 Hz, on two 0.8 x 0.3 m force plates (AMTI, MA, USA). Three-dimensional kinematic data were simultaneously (time synchronized) recorded with the force data in Nexus (Vicon, Oxford Metrics, UK) using 6 optoelectronic cameras, sampling at 100 Hz.

Marker trajectories and force data were both filtered using a 4th order low pass Butterworth filter with a cut off frequency of 20 Hz [34]. Touch-down and take-off events were created when the vertical force crossed a 20 N threshold. The external knee flexion moment (KFM), external hip flexion moment (HFM) and external knee abduction moment (KAM) were calculated across the entire stance phase using inverse dynamics. These moments were normalized to body weight (kg) and height (m). The HFM and KFM were evaluated because

females exhibit relatively lower HFM and higher KFM during drop jumps than males, which is suggested to be related to increased injury risk [7,8,14,35]. The KAM was included because this parameter has been associated with an increased patellofemoral [24] and anterior cruciate ligament [25] injury risk. Furthermore, sagittal plane landing strategies can be related to frontal plane knee moments [14]. The average of 3 trials was calculated for all outcomes for each participant.

In addition to the 3D motion analysis, sagittal plane movements were simultaneously captured with a standard digital video camera (Sony DCR-HC20E) sampling at 50 Hz. The camera was placed on a tripod perpendicular to the sagittal plane, at a height of 60 cm and a distance of 3.5 m. The video recordings were analyzed using a commercial software package (Dartfish software 6.0, Fribourg, Switzerland). The deepest initial landing position, defined as the time point where no downward or upward movement occurred at the hip, knee and ankle, was determined visually and was used to take a digital picture of each trial. This deepest position was previously also assessed in studies where 2D video analysis was used in the frontal plane [3-6]. Furthermore, the deepest position is the easiest (least debatable) time point to reproduce in clinical practice using 2D video analysis. Similar to the methodology of Dingenen et al. [3] in the frontal plane, all sagittal plane angles were drawn on the same digital picture. All angles were drawn by the same tester.

For the 2D analysis, the reflective markers on the acromioclavicular joint, trochanter major, lateral femoral epicondyle, lateral malleolus and metatarsal head V were used to assist manual digitization. The hip flexion angle was the angle between the line formed by the acromioclavicular joint and the greater trochanter, and a second line connecting the greater trochanter to the lateral femoral epicondyle (Figure 1 ABC) [36]. The knee flexion angle was the angle between the line formed by the greater trochanter and the lateral femoral epicondyle,

and a second line connecting the lateral femoral epicondyle and the lateral malleolus (Figure 1 DEF) [11,36]. The ankle dorsiflexion angle was the angle between the line formed by the lateral femoral epicondyle and the lateral malleolus, and a second line connecting the lateral malleolus and metatarsal head V (Figure 1 GHI). Smaller hip flexion, knee flexion and ankle dorsiflexion angles represent respectively more hip flexion, knee flexion and ankle dorsiflexion.

To assess the intra- and intertester reliability of the hip flexion, knee flexion and ankle dorsiflexion angle measurements, the 2D videos of 15 randomly chosen participants (10 soccer, 3 handball, 2 volleyball) were analyzed twice by two independent testers. The same videos were used to make a new digital picture to perform the second measurement of the angles [3]. Intertester reliability was calculated for both the first and the second measure. The testers were blinded to the results of each other. A 7-day interval was used between the repeated measures [3,36]. The average angle of 3 valid trials was used to calculate the absolute differences and intraclass correlation coefficients ($ICC_{2,1}$). The standard error of measurement (SEM) and smallest detectable difference (SDD) were calculated using the formulas $SD \cdot \sqrt{1-ICC}$ and $1.96 \cdot SEM \cdot \sqrt{2}$ respectively [37]. These statistical analyses were performed using IBM SPSS Statistics for Windows, Version 19.0, Armonk, NY: IBM Corp., USA. All 2D kinematic outcomes showed an excellent intra- and intertester reliability, with high ICC values (0.98-1.00) and small absolute differences (0.3-1.6°), SEM (0.0-0.9°) and SDD (0.0-2.5°) (Appendices A and B). Malfait et al. [28] recently showed that the 3D outcomes in our study during DVJ can be measured in a reliable way.

2.3 Data analysis

Firstly, one-dimensional statistical parametric mapping (SPM1D) linear regression was used (Enthought Canopy, v.1.0.3.1262) [38,39] to examine the relationships between the peak 2D angles and 3D moment components during the stance phase for each task. Full details including test statistic calculation, critical threshold identification and statistical inference are provided elsewhere [38,40] and hence are described briefly. The advantage of this particular analysis is that it determines the strength of the relationship between the 2D predictor variable at each time node in the 3D moment response variable. The 2D predictor variables were regressed against the 3D moment curves across subjects, using one value (the mean) for each subject. This analysis was repeated for three 2D angles and three 3D moment components, hence $\alpha = 0.0055$ ($\alpha = 0.05$ corrected for 9 regressions) was used to reduce the likelihood of a type 1 error. The resulting SPM{t} curve indicated if the relationship between the 2D and 3D variables was statistically significant. A supra-threshold cluster indicated that a relationship of that magnitude would be produced by random curves in only 0.55% of repeated tests.

Second, we established if there were any differences in 2D angles (peak values) or 3D moments (across the entire stance phase) between DVJ and SLDVJ, as the temporal relationships between 2D and 3D data may be influenced by the substantially different physical demands during double-leg and single-leg tests [41]. Furthermore, these comparisons may help to clarify possible different 2D-3D relationships between both tests.

All mean 2D angles showed a normal distribution (Shapiro-Wilk) ($P > 0.05$). Dependent t-tests were used to compare the 2D angles between DVJ and SLDVJ. Alpha was set at $P <$

0.05. These statistical analyses were performed using IBM SPSS Statistics for Windows, Version 19.0, Armonk, NY: IBM Corp., USA.

To compare the 3D moments of the DVJ and SLDVJ, SPM1D was used [38]. The mean differences between DVJ and SLDVJ curves were calculated for the whole stance phase for each joint moment. Each difference curve was then analyzed with a one-sample t-test with alpha set at 0.05. The smoothness of the resulting statistic $SPM\{t\}$ was estimated based on its average temporal gradient, and the critical threshold was calculated, above which only 5% of random curves would traverse. Finally, the probability with which supra-threshold regions of the $SPM\{t\}$ curve could have resulted from repeated samplings of equally smooth random curves were estimated.

3. Results

3.1 Correlational analysis: statistical parametric mapping analysis

For DVJ, hip flexion was significantly negatively related to HFM ($P < 0.0001$), and positively related to KFM ($P < 0.0055$) and KAM ($P < 0.0001$) during the time frames where peak joint moments occurred (Figure 2). During ~ 12-15% and ~ 85-95% of the stance phase, hip flexion was significantly negatively related to KFM ($P < 0.0001$). Knee flexion was significantly negatively related to HFM during ~ 35-40% and ~ 60-80% of the stance phase ($P < 0.0001$), to KFM during ~ 12-15% ($P < 0.01$) and ~ 85-95% of the stance phase ($P < 0.0001$) and to KAM during ~ 80-90% of the stance phase ($P < 0.001$). No significant relationships were found between ankle dorsiflexion and 3D moments.

For SLDVJ, hip flexion was significantly negatively related to HFM ($P < 0.0001$) and positively related to KFM ($P < 0.001$) during the time frames where peak joint moments occurred (Figure 3). During ~ 80-90% of the stance phase, hip flexion was significantly

negatively related to KFM ($P < 0.001$). Knee flexion was significantly negatively related to HFM during ~ 55-80% of the stance phase ($P < 0.0001$) and to KFM during ~ 80-95% of the stance phase ($P < 0.001$). No significant relationships were found between any 2D angle and KAM, and between ankle dorsiflexion and 3D moments.

3.2 Differences between tests

For the 2D angles, significantly decreased hip flexion, knee flexion and ankle dorsiflexion (indicated by larger angles) were found during SLDVJ compared to DVJ ($P < 0.05$) (Figure 4).

For the 3D moments, significantly increased HFM and KFM were found in SLDVJ compared to DVJ during the largest part of the stance phase ($P < 0.0001$). Only during approximately the first and last 10% of the stance phase, KFM was significantly higher in DVJ ($P < 0.0001$). The KAM was significantly smaller during almost the entire stance phase in SLDVJ ($P < 0.0001$) (Figure 5).

4. Discussion

The main goal of the present study was to examine the temporal relationships between 2D measured sagittal plane kinematics and 3D joint moments during the DVJ and SLDVJ. As the timing of these possible relationships was not known before the start of the study, we used SPM1D to analyze when the peak 2D joint excursions were related to the 3D joint moments, hereby including the moments across the whole stance phase and avoiding potential bias by focusing only on specific time intervals, for example when peak moments occurred. The most

consistent finding was that hip flexion at the deepest landing position was significantly negatively related to HFM and positively related to KFM for both the DVJ and SLDVJ during the time frames corresponding to peak joint moments. The definition of the hip flexion angle in our study implies that larger hip flexion angles represent a more erect trunk position. As a consequence, the center of mass may be positioned more posteriorly and increase the lever arm for the vertical ground reaction force vector at the knee, while decreasing the lever arm at the hip, thereby increasing the external knee flexion moment and decreasing the external hip flexion moment respectively [42]. These findings are in accordance with studies where only 3D analyses were used [13,15]. Our study is the first to relate these joint moments to peak 2D angular excursions in the sagittal plane.

The external moments reported in our study need to be counterbalanced by equal and opposite internal joint moments. Internal joint moments are caused by forces within the body itself, such as muscle forces and tensile forces of capsuloligamentous joint structures [15]. However, it is important to realize that individual tissue loading (such as the anterior cruciate ligament or patellar tendon) cannot be derived from these joint moments [15]. Nevertheless, examining these joint moments may still improve our understanding how specific muscle groups contribute to control and produce movement. For example, landing with increased KFM and decreased HFM, a landing strategy that based on our results can be identified with less hip flexion, is characterized by an overreliance on the quadriceps muscles [13,16], while decreasing the reliance on the hip extensors to attenuate the ground reaction forces [14,35]. A decreased gluteus maximus muscle activity in combination with an increased quadriceps muscle activity was previously reported during single-leg landings in female athletes compared to male athletes [43]. The gluteus maximus is considered to be the most important hip extensor, but due to its anatomical characteristics, this muscle also functions to abduct and

externally rotate the femur [44]. The more erect trunk position and associated sagittal plane moment distribution in the direction of the knee and away from the hip (a “hip avoidance” landing strategy) may put the hip extensors in a mechanical disadvantage for producing force [45], hereby limiting the capacity of these muscles to modulate trunk and lower extremity biomechanics [8]. At the knee, the increased external flexion moment and associated increased quadriceps activity induced by the more erect trunk position were previously related to increased anterior tibial shear forces [17], patellofemoral joint reaction forces [18,19], and patellar tendon forces [20], which are believed to be important factors in the development of respectively anterior cruciate ligament injuries [21], patellofemoral pain [22] and patellar tendinopathy [23]. Next to this sagittal plane moment distribution, this hip avoidance landing strategy may also play a role in frontal plane knee moment modulation. In our study, hip flexion was also significantly related to KAM during the DVJ, again during the time frame where peak moments occurred. These relations indicate that participants who used less hip flexion during the deepest landing position of the DVJ relied more on frontal plane knee moments to decelerate the body center of mass. This rather passive movement strategy has previously been suggested in female athletes [14,27,35]. The association between sagittal motion and frontal plane knee moments is of particular interest, as increased peak KAM during the DVJ has been associated with an increased patellofemoral [24] and anterior cruciate ligament [25] injury risk, further supporting the assumption that hip and trunk movements are important when assessing knee joint injury risk [8,26,27]. In contrast with DVJ, no significant relationships were found between hip flexion and KAM during SLDVJ. This may be explained by the substantially different physical demands during double-leg and single-leg tests [41] which were performed from different heights. Decreased hip flexion, knee flexion and ankle dorsiflexion and increased hip and knee flexion moments were found during SLDVJ compared to DVJ, while KAM was significantly smaller, especially during the

time frames where peak joint moments occurred. A more erect landing pattern may limit the ability to effectively attenuate ground reaction forces [13], thereby contributing to the higher sagittal plane moments during SLDVJ, despite the lower height of the box. With the smaller base of support and all body weight on one leg during the SLDVJ, there is likely a need to stabilize the knee carefully as not to leave the opportunity to medially collapse under the high flexion loads. These different landing strategies were previously also reported in a study where the DVJ was compared with a single-leg landing task [41].

In contrast with the hip flexion angle, the knee flexion angle was not significantly related to KFM and KAM during the time frames where highest moments occurred in either of the tests. On the other hand, we found that a deeper knee flexion position was related to increased HFM. This finding may be related to the fact that increased knee flexion is generally accompanied by concomitant increased hip flexion [46]. However, this coupled motion may be an oversimplification of the coordination between the knee and hip [17]. A variety of different whole body movement strategies may exist to perform jump-landing tasks (Figure 1). Some participants in the current study used a landing pattern with less hip and knee flexion (erect landing pattern) (Figure 1 ADG), others used a pattern where the trunk was still relatively erect, while the knee was more flexed (knee dominant landing pattern) (Figure 1 BEH) and others used increased flexion in both the hip and the knee (flexed landing pattern) (Figure 1 CFI). Our results suggest that the amount of hip flexion seems to be the most dominant predictor for knee joint moments. This supports literature where both the erect [26,27] and knee dominant landing patterns [7,8,11,23] are suggested to be related to increased knee injury risk.

The ankle joint may be an important link within the functioning of the kinetic chain. Decreased ankle dorsiflexion range of motion may increase the risk to sustain patellar

tendinopathy [47] and anterior cruciate ligament injuries [48]. However, no significant results were found between ankle dorsiflexion and 3D moments in our study. The smaller variation and slightly lower reliability of the measurement of this angle may provide feasible explanations. Furthermore, reducing motion analysis of the ankle-foot complex towards one angle between two rigid segments using 2D video analysis may be too simplified, as the multi-segmental and multi-planar function cannot be assessed.

The underlying reasons to use the aforementioned biomechanically less optimal landing patterns are probably associated with multiple factors within the kinetic chain. A diminished hip extensor/knee extensor strength ratio was found to be related to the tendency to land with higher KFM relative to HFM [49]. However, it remains unclear whether these strength deficits are the cause or the consequence of these less optimal landing patterns. It may be possible that these landing patterns are the result of a learned motor program that the athlete has adopted over time, rather than the inability to produce force [42]. Movement re-education is therefore considered to be an essential component of effective injury prevention programs [50]. Based on our results, increasing the amount of hip and trunk flexion should be the primary focus to avoid high risk knee moments.

Some limitations of our study need to be addressed. We did not measure lower extremity muscle activation, strength, flexibility or joint range of motion. Therefore, we cannot directly relate the reported altered landing patterns to certain deficits in these parameters. However, this was not the goal of the current study. Three-dimensional kinematic data were measured with 6 cameras at a sample frequency of 100 Hz, which is relatively low compared to other studies focusing on jump-landing tasks [24,25,28,35,49]. However, this was the maximal sample rate of the cameras for the full field of view and resolution. Increasing the sample rate would have induced a loss of image resolution, which would have had a greater impact on the

quality of our data than increasing the measuring frequency above 100 Hz. It is important to note that reporting a relation between 2D angles and 3D joint moments in this cross-sectional study is not the same as directly predicting injury risk, or of providing normative threshold values [4]. Future prospective studies should investigate whether 2D measured kinematics can predict knee injuries.

5. Conclusion

The results of the current study show that the amount of hip flexion at the deepest landing position of DVJ and SLDVJ, measured with simple 2D video analysis, was significantly related to HFM and KFM for both tests, and KAM for DVJ during the time frames where peak joint moments occurred, while the amount of knee flexion was only related to HFM. These findings are important to translate findings from laboratory settings towards clinical practice, and provide further evidence that lower extremity joints interact within a kinetic chain to control dynamic movements. In addition to the 2D frontal plane video analysis which is mostly performed, 2D sagittal plane video analysis offers additional opportunities to identify less optimal landing patterns with a clinical-friendly method.

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REFERENCES

- [1] Agel J, Arendt EA, Bershadsky B. Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. *Am J Sports Med* 2005;33:524-30.
- [2] Boling M, Padua D, Marshall S, Guskiewicz K, Pyne S, Beutler A. Gender differences in the incidence and prevalence of patellofemoral pain syndrome. *Scand J Med Sci Sports* 2010;20:725-30.
- [3] Dingenen B, Malfait B, Vanrenterghem J, Verschueren SM, Staes FF. The reliability and validity of the measurement of lateral trunk motion in two-dimensional video analysis during unipodal functional screening tests in elite female athletes. *Phys Ther Sport* 2014;15:117-23.
- [4] Mizner RL, Chmielewski TL, Toepke JJ, Tofte KB. Comparison of 2-dimensional measurement techniques for predicting knee angle and moment during a drop vertical jump. *Clin J Sport Med* 2012;22:221-7.
- [5] Munro A, Herrington L, Carolan M. Reliability of two-dimensional video assessment of frontal-plane dynamic knee valgus during common athletic screening tasks. *J Sport Rehabil* 2012;21:7-11.
- [6] Stensrud S, Myklebust G, Kristianslund E, Bahr R, Krosshaug T. Correlation between two-dimensional video analysis and subjective assessment in evaluating knee control among elite female team handball players. *Br J Sports Med* 2011;45:589-95.

- [7] Hashemi J, Breighner R, Chandrashekar N, Hardy DM, Chaudhari AM, Shultz SJ et al. Hip extension, knee flexion paradox: a new mechanism for non-contact ACL injury. *J Biomech* 2011;44:577-85.
- [8] Powers CM. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *J Orthop Sports Phys Ther* 2010;40:42-51.
- [9] Quatman CE, Quatman-Yates CC, Hewett TE. A 'plane' explanation of anterior cruciate ligament injury mechanisms: a systematic review. *Sports Med* 2010;40:729-46.
- [10] Mottram S, Comerford M. A new perspective on risk assessment. *Phys Ther Sport* 2008;9:40-51.
- [11] Mann KJ, Edwards S, Drinkwater EJ, Bird SP. A lower limb assessment tool for athletes at risk of developing patellar tendinopathy. *Med Sci Sports Exerc* 2013;45:527-33.
- [12] Myer GD, Ford KR, Khoury J, Succop P, Hewett TE. Development and validation of a clinic-based prediction tool to identify female athletes at high risk for anterior cruciate ligament injury. *Am J Sports Med* 2010;38:2025-33.
- [13] Shimokochi Y, Ambegaonkar JP, Meyer EG, Lee SY, Shultz SJ. Changing sagittal plane body position during single-leg landings influences the risk of non-contact anterior cruciate ligament injury. *Knee Surg Sports Traumatol Arthrosc* 2012;21:888-97.

- [14] Pollard CD, Sigward SM, Powers CM. Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clin Biomech* (Bristol, Avon) 2010;25:142-6.
- [15] Shimokochi Y, Yong LS, Shultz SJ, Schmitz RJ. The relationships among sagittal-plane lower extremity moments: implications for landing strategy in anterior cruciate ligament injury prevention. *J Athl Train* 2009;44:33-8.
- [16] Malfait B, Dingenen B, Staes F, Vanrenterghem J, Verschueren S. Differences in neuromuscular activity of quadriceps and hamstrings with respect to different landing patterns in female athletes. *Br J Sports Med* 2014;48:631.
- [17] Yu B, Lin CF, Garrett WE. Lower extremity biomechanics during the landing of a stop-jump task. *Clin Biomech* (Bristol, Avon) 2006;21:297-305.
- [18] van Eijden TM, Weijs WA, Kouwenhoven E, Verburg J. Forces acting on the patella during maximal voluntary contraction of the quadriceps femoris muscle at different knee flexion/extension angles. *Acta Anat (Basel)* 1987;129:310-4.
- [19] Ho KY, Blanchette MG, Powers CM. The influence of heel height on patellofemoral joint kinetics during walking. *Gait Posture* 2012;36:271-5.
- [20] Nisell R, Ekholm J. Patellar forces during knee extension. *Scand J Rehabil Med* 1985;17:63-74.
- [21] Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slaughterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res* 1995;13:930-5.

- [22] Dye SF. The pathophysiology of patellofemoral pain: a tissue homeostasis perspective. *Clin Orthop Relat Res* 2005;100-10.
- [23] Edwards S, Steele JR, McGhee DE, Beattie S, Purdam C, Cook JL. Landing strategies of athletes with an asymptomatic patellar tendon abnormality. *Med Sci Sports Exerc* 2010;42:2072-80.
- [24] Myer GD, Ford KR, Barber Foss KD, Goodman A, Ceasar A, Rauh MJ et al. The incidence and potential pathomechanics of patellofemoral pain in female athletes. *Clin Biomech (Bristol, Avon)* 2010;25:700-7.
- [25] Hewett TE, Myer GD, Ford KR, Heidt RS, Jr., Colosimo AJ, McLean SG 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.
- [26] Aerts I, Cumps E, Verhagen E, Verschueren J, Meeusen R. A systematic review of different jump-landing variables in relation to injuries. *J Sports Med Phys Fitness* 2013;53:509-19.
- [27] Mendiguchia J, Ford KR, Quatman CE, Alentorn-Geli E, Hewett TE. Sex differences in proximal control of the knee joint. *Sports Med* 2011;41:541-57.
- [28] Malfait B, Sankey S, Azidin RM, Deschamps K, Vanrenterghem J, Robinson MA et al. How reliable are lower limb kinematics and kinetics during a drop vertical jump? *Med Sci Sports Exerc* 2014;46:678-85.

- [29] Dingenen B, Malfait B, Vanrenterghem J, Robinson M, Verschueren S, Staes F. Are two-dimensional measured sagittal plane kinematics related to three-dimensional joint loading during the drop vertical jump test? *Br J Sports Med* 2014;48:585.
- [30] Cappozzo A, Catani F, Della Croce U, Leardini A. Position and orientation in-space of bones during movement - anatomical frame definition and determination. *Clin Biomech (Bristol, Avon)* 1995;10:171-8.
- [31] Schwartz MH, Rozumalski A. A new method for estimating joint parameters from motion data. *J Biomech* 2005;38:107-16.
- [32] Besier TF, Sturnieks DL, Alderson JA, Lloyd DG. Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *Journal of Biomechanics* 2003;36:1159-68.
- [33] Dempster WT, Gaughran GR. Properties of body segments based on size and weight. *Am J Anat* 1967;120:33-54.
- [34] 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.
- [35] Sigward SM, Pollard CD, Powers CM. The influence of sex and maturation on landing biomechanics: implications for anterior cruciate ligament injury. *Scand J Med Sci Sports* 2011;22:502-9.
- [36] Norris BS, Olson SL. Concurrent validity and reliability of two-dimensional video analysis of hip and knee joint motion during mechanical lifting. *Physiother Theory Pract* 2011;27:521-30.

- [37] Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Strength Cond Res* 2005;19:231-40.
- [38] Pataky TC. One-dimensional statistical parametric mapping in Python. *Comput Methods Biomech Biomed Engin* 2012;15:295-301.
- [39] Vanrenterghem J, Venables E, Pataky T, Robinson MA. The effect of running speed on knee mechanical loading in females during side cutting. *J Biomech* 2012;45:2444-9.
- [40] Pataky TC. Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *J Biomech* 2010;43:1976-82.
- [41] Harty CM, DuPont CE, Chmielewski TL, Mizner RL. Intertask comparison of frontal plane knee position and moment in female athletes during three distinct movement tasks. *Scand J Med Sci Sports* 2011;21:98-105.
- [42] Sigward SM, Pollard CD. Proximal risk factors for ACL injury: role of the hip. In: Noyes FR, Barber-Westin SD, editors. *ACL injuries in the female athlete*, Berlin: Springer-Verlag; 2012, p. 185-201.
- [43] Zazulak BT, Ponce PL, Straub SJ, Medvecky MJ, Avedisian L, Hewett TE. Gender comparison of hip muscle activity during single-leg landing. *J Orthop Sports Phys Ther* 2005;35:292-9.
- [44] Neumann DA. Kinesiology of the hip: a focus on muscular actions. *J Orthop Sports Phys Ther* 2010;40:82-94.

- [45] Kulas A, Zalewski P, Hortobagyi T, DeVita P. Effects of added trunk load and corresponding trunk position adaptations on lower extremity biomechanics during drop-landings. *J Biomech* 2008;41:180-5.
- [46] Blackburn JT, Padua DA. Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clin Biomech (Bristol, Avon)* 2008;23:313-9.
- [47] Backman LJ, Danielson P. Low range of ankle dorsiflexion predisposes for patellar tendinopathy in junior elite basketball players: a 1-year prospective study. *Am J Sports Med* 2011;39:2626-33.
- [48] Boden BP, Torg JS, Knowles SB, Hewett TE. Video analysis of anterior cruciate ligament injury: abnormalities in hip and ankle kinematics. *Am J Sports Med* 2009;37:252-9.
- [49] Stearns KM, Keim RG, Powers CM. Influence of relative hip and knee extensor muscle strength on landing biomechanics. *Med Sci Sports Exerc* 2013;45:935-41.
- [50] Herman DC, Onate JA, Weinhold PS, Guskiewicz KM, Garrett WE, Yu B et al. The effects of feedback with and without strength training on lower extremity biomechanics. *Am J Sports Med* 2009;37:1301-8.

Fig 1

Fig 2

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Fig 4

Fig 5

FIGURE CAPTIONS**Figure 1:**

Examples of three performances of the drop vertical jump. The participant in figures ADG uses an erect landing pattern with decreased hip flexion (A), knee flexion (D) and ankle dorsiflexion (G). The participant in figures BEH uses a knee dominant landing pattern, with decreased hip flexion (B), but increased knee flexion (E) and ankle dorsiflexion (H). The participant in figures CFI uses a flexed landing pattern, with increased hip flexion (C), knee flexion (F) and ankle dorsiflexion (I).

Figure 2:

Characterization of the temporal relationships between hip flexion (HF), knee flexion (KF), ankle dorsiflexion (ADF) and external hip flexion moment (HFM), external knee flexion moment (KFM) and external knee abduction moment (KAM) during the drop vertical jump using SPM1D. The $SPM\{t\}$ curves are shown over the stance phase, and the magnitude of the $SPM\{t\}$ curve describes the strength and direction of the linear angle-moment relations. Where the $SPM\{t\}$ curve exceeds the critical threshold (dotted line), this area is shaded and a significant relationship is present. *P*-values are provided for each supra-threshold cluster.

Figure 3:

Characterization of the temporal relationships between hip flexion (HF), knee flexion (KF), ankle dorsiflexion (ADF) and external hip flexion moment (HFM), external knee flexion moment (KFM) and external knee abduction moment (KAM) during the single-leg drop

vertical jump using SPM1D. The $SPM\{t\}$ curves are shown over the stance phase, and the magnitude of the $SPM\{t\}$ curve describes the strength and direction of the linear angle-moment relations. Where the $SPM\{t\}$ curve exceeds the critical threshold (dotted line), this area is shaded and a significant relationship is present. *P*-values are provided for each supra-threshold cluster.

Figure 4:

Statistical comparison of the drop vertical jump (DVJ) and single-leg drop vertical jump (SLDVJ) for the two-dimensional measured hip flexion (HF), knee flexion (KF) and ankle dorsiflexion (ADF) angles.

Figure 5:

Statistical comparison of the drop vertical jump (DVJ) and single-leg drop vertical jump (SLDVJ) for the 3D joint moments. The upper panels (a, b, c) show the means and standard deviations of the external hip flexion moment (HFM), external knee flexion moment (KFM) and external knee abduction moment (KAM) over the stance phase. All moments were normalized to body weight (BW) and height (ht). Flexion (Flex) and abduction (Abd) moments are presented as positive values, while extension (Ext) and adduction (Add) moments are presented as negative values. The lower panels (d, e, f) show the $SPM\{t\}$ curves over the stance phase. Where the $SPM\{t\}$ curve exceeds the critical threshold (dotted line), this area is shaded and a significant difference is present between the corresponding moment curves in the panel above. *P*-values are provided for each supra-threshold cluster.