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Reliability of knee biomechanics during a vertical drop jump in elite female athletes

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The authors declare that there are no conflicts of interest.

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Abstract (250 words)

The purpose of the study was to assess the within-session and between-session reliability of knee kinematics and kinetics in a vertical drop jump task among elite female handball and football athletes. Specifically, we aimed to quantify the within-session waveform consistency and between-session consistency of the subject ranking for a variety of knee kinematics and kinetics.

Forty-one elite female handball and football (soccer) athletes were tested in two sessions. The reliability of three-dimensional knee biomechanical measurements was quantified by the intra-class correlation, Spearman's rank correlation, and typical error. All the selected discrete variables achieved excellent within-session reliability (ICC > 0.87). The typical error of valgus angles, internal rotation angles, and internal rotation moment was constant throughout the whole stance phase. For between-session reliability, the selected discrete variables achieved good to excellent reliability (ICC > 0.69), except peak internal rotation moment (ICC = 0.40). All between-session rank correlation coefficients ranged from 0.56 to 0.90. Most of the discrete variables achieved good to excellent reliability in both within-session and between-session analysis. Moreover, moderate to strong between-session consistency of subject rankings was found, implying that the measurements assessed during the vertical drop jump demonstrate sufficient reliability to be used in both single-session and multiple-session studies.

1. Introduction

Vertical drop jump tasks have been widely used in anterior cruciate ligament (ACL) injury-related research in the last decade. Three-dimensional knee kinematics and kinetics, quantified using marker-based motion analysis systems, have been used to identify potential risk factors for ACL injuries [1,2]. Furthermore, knee kinematics and kinetics in vertical drop jumps are utilized for ACL injury risk assessment [2,3] and evaluation of training interventions [4,5].

Previous research has investigated both within-session and between-session reliability of various knee biomechanical variables in vertical drop jump tasks [6,7]. Ford et al. [6] utilized the intra-class correlation coefficient (ICC) and typical error of various discrete biomechanical variables to quantify the between-session reliability. The majority of the knee kinematic and kinetic variables were shown to have fair to excellent reliability within- (ICC from 0.67 to 0.99) and between-sessions (ICC from 0.59 to 0.92) in young female high school athletes [6]. Malfait et al. [7] assessed the within-session reliability of the knee kinematics variables, and showed that the variability ranged from 1.1° to 3.8°.

The ICC is commonly used to describe reliability, however, there is considerable confusion concerning both the calculation and interpretation of the ICC [8]. The ICC will give high reliability when the subject range is large, even if trial-to-trial variability is large [8,9]. Spearman's rank correlation will be unaffected by the range in the variable as it transforms the measurements to the ranking domain for the correlation calculation thus is less sensitive to between-subject variability. Spearman's rank correlation coefficient can theoretically provide additional information on reliability, in particular on subject rankings.

The coefficient of multiple correlations (CMC) has been used to assess the waveform reliability [6]. However, CMC coefficient measures are underestimating the reliability for small motions [10] and are generally insensitive to systematic error [11]. An alternative to the CMC, the waveform reliability can be quantified as the typical error of every time point. With this temporal presentation, the movement variability can be further described in a specific region such as initial contact or mid-stance. Using this approach, we could detect variation between sessions and attribute them to a specific phase of the movement. For example, a previous study found that most of the variability of the kinetics measurements were around impact (0%–20% of contact phase) [7]. The current study would use this approach to present waveform reliability.

The low number of participants in the previous reliability studies is a major concern [12]. Methodology studies of reliability in sports medicine suggest that such studies should contain a minimum of 40 subjects [13]. The reliability of vertical drop jump tasks have, up until now, only been investigated in very limited populations, i.e. one study on 8 recreational athletes [7] and one on 11 high school athletes [6]. Likewise, the reliability of medial knee displacement was only reported from a study with five subjects [14].

Furthermore, previous studies have not investigated the reliability of vertical drop jump task in homogenous elite populations. Elite female handball and football cohorts are of particular interest, knowing that the risk of sustaining ACL injuries is higher, compared with other groups of athletes [15,16].

The aim of the present study was to assess the within-session and between-session reliability of knee kinematics and kinetics in a vertical drop jump task among elite female handball and football athletes. Specifically, we aimed to quantify the within-session waveform error of measurements and between-session consistency of the subject measurements and rankings.

2. Methods

2.1 Subjects. Forty-one elite female handball and football (soccer) athletes (mean ± SD: 22 ± 4 yrs old, 168 ± 5 cm, 66 ± 8 kg) performed vertical drop jumps in our biomechanics laboratory. The Regional Ethics Committee approved the study and all subjects provided signed informed consent forms.

2.2 Sample size calculation. Sample size calculation was performed using the formula of Shoukri et al. [17]. The formula is specifically designed for reliability studies by setting the limit of the confidence interval width of the reliability coefficient. The width of the confidence interval was set to be 0.2 based on the reliability coefficient reported by Ford and colleagues [6]. Based on this, with three repeated trials and mean reliability coefficient value of 0.8, the formula gave a minimum sample size requirement of 37 subjects.

2.3 Design and protocol. Subjects were tested during pre-season in two separate sessions, on average separated by two weeks. We instructed subjects to drop off a 30 cm box and perform a maximal jump upon landing with their feet on separate force platforms (AMTI LG6-4-1, Watertown, Massachusetts, USA). They were allowed to have three practice trials and at least three valid trials were collected for each player. At least two test operators observed the execution of the jump. If sub-maximal effort was suspected, or when jumping instead of dropping off the box (i.e. increasing the vertical center of mass position at take-off from the box), we asked the subject to repeat the jump. Players were encouraged to jump with maximal effort for every jump.

Subjects wore indoor sport shoes, shorts and a sports bra. Thirty-seven reflective markers were attached over anatomical landmarks on the legs, arms and torso [18]. One experienced physiotherapist, with several years practice for marker placement, was employed for skin marker placement in both sessions.

We used a 480 Hz 16-camera system (Oqus 4, Qualisys, Gothenburg, Sweden) to capture motion, while we recorded ground reaction forces using two force platforms collecting at 960 Hz (AMTI LG6-4-1, Watertown, Massachusetts, USA). We calibrated the motion analysis system according to guidelines from the manufacturer, and calculated and tracked marker trajectories using the Qualisys Track Manager (Qualisys, Gothenburg, Sweden).

We defined the contact phase 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 [19], using a 15 Hz cut-off [18].We calculated the hip joint center using the method proposed by Bell et al. [20], with the anterior-posterior position of the hip joint decided by the anterior-posterior position of the marker over the greater trochanter. Furthermore, we defined the knee joint center according to Davis [21], and the ankle joint center according to Eng & Winter [22]. Anatomical coordinate systems of the thigh and shank were determined from the static calibration trials. We defined the vertical axis in the direction from the distal to the 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 axes. Consequently, all segments had neutral internal/external rotation in the static calibration trial. We obtained technical, dynamic thigh and shank segment coordinate systems using an optimization procedure involving singular value decomposition [23].

We estimated inertia parameters based on 46 measures of segment heights, perimeters and widths using a modified Yeadon's method [24], with hand and foot parameters calculated with the method of Zatsiorsky & Seluyanov [25]. We calculated hip and knee joint moments with inverse dynamics using recursive Newton-Euler equations of motion as described by Davis et al. [21] and projected onto the three rotational axes of the joint according to the joint coordinate system standard [26].

We used the Grood & Suntay [26] convention for calculating joint angles from the marker-based motion analysis. Medial knee displacement was introduced to quantify the valgus lower limb alignment which is believed to increase the risk of ACL rupture [1,3]. We calculated medial knee position as the perpendicular distance between the knee joint center and the line joining the ankle and hip joint centers, projected on the frontal plane. The difference between the perpendicular position at the initial foot contact and the peak value was defined as the medial knee displacement. An advantage of this convention compared with a pure knee separation measure is that we can assess knee control individually for the left and right leg. Furthermore, this measure is simpler than skin marker based 3D valgus measurements, which is useful in applied clinical settings [27]. We ran all calculations using custom Matlab scripts (MathWorks Inc., Natick, Massachusetts, USA).

2.4 Statistical analysis. For simplicity, only the measurements from the right leg were used for analyses. Each trial was time-normalized from 0% to 100% of the stance phase. For every time point, we calculated the typical error based on three trials from each subject. The typical error was calculated from the standard deviation of inter-trial differences divided by the square root of 2 [28]. The typical error represented 52% of test-retest differences of a subject in the sample group [28]. The between-session typical error was calculated based on the mean value of three trials in each session. Moreover, the mean curves and standard deviation were computed to represent the motion and between-subject variability.

We report the mean, standard deviation, and typical error of both within and between-session measurements. The ICC values for within-session (ICC(3,k)) and between-session (ICC(3,1)) were both computed. The ICC classifications of Fleiss [29] (less than 0.4, poor; between 0.4 and 0.75, fair to good; and greater than 0.75, excellent) were used to describe the range of ICC values. To assess the consistency of subject ranking between-sessions, Spearman’s rank correlation coefficients were calculated based on the mean measurement from sessions 1 and 2. The classifications of Zou et al. [30] (greater than 0.5, moderately positive; greater than 0.8, strongly positive) were used to interpret the rank correlation coefficients. Paired t-tests were employed to assess the significant difference of the mean measurement between sessions. Cohen's *d* was computed to assess the effect size of the mean differences. Statistical significance was set at $p \leq 0.05$. Statistical analyses were performed using SPSS 18 (SPSS Inc., Chicago, IL, USA) and the statistics toolbox of Matlab (MathWorks Inc., Natick, MA, USA).

3. Results

All the selected discrete variables achieved excellent within-session reliability with all ICC values greater than 0.87 (Table 1). The typical errors were generally small. The errors related to the valgus angles were < 1.0°.

The within-session typical error of the knee valgus, internal rotation angle and internal rotation moment was relatively constant throughout the whole stance phase (Fig 1 and 2). We observed an increase in typical error during the mid-stance for the knee flexion angle, medial knee displacement, knee flexion moment, and knee valgus moment. The maximal typical error for the vertical ground reaction force was found in the first 15% of the stance phase.

The between-session ICC values for most of the selected discrete variables achieved good to excellent between-session reliability (Table 1). However, peak internal rotation moment displayed only fair between-session reliability with an ICC value of 0.40. All the rank correlation coefficients demonstrated positive correlation on the between-session subject ranking. Peak flexion moment, peak valgus angle, peak internal rotation angle, medial knee displacement and jump height showed a strong between-session consistency with rank correlation coefficients greater than 0.8 [30]. The flexion angle at initial contact, peak flexion angle, knee flexion range of motion, peak internal rotation angle and the medial knee displacement were significantly different between sessions ($p<0.05$). However, all the Cohen's *d* values were smaller than 0.31, indicating that the effect sizes of the mean differences were small.

Differences in typical error waveforms were observed between sessions (Figure 1 and 2). The knee flexion angle, medial knee displacement, flexion moment and valgus moment had a higher typical error in the mid-stance phase in session 2.

4. Discussion

In the current study, we assessed the reliability of knee kinematics and kinetics in a vertical drop jump task in elite female handball and football athletes. Most of the discrete knee biomechanical variables achieved good to excellent reliability in both within-session and between-session analyses. Moreover, we found a strong between-session consistency of subject measurements and rankings, implying that the estimates could reliably reproduce the testing results in both single-session and multiple-session studies. Valgus and internal rotation angles were highly reliable while the knee flexion angle can vary considerably within-session in some subjects.

The within-session reliability (ICC 0.87 to 0.98) was, in general, better than between-session reliability (ICC 0.40 to 0.90). The lower reliability between sessions is likely a result of variability in skin marker placement and changes in subject movement. In a recent methodological study, it was concluded that even small changes in skin marker placement resulted in a significant change in the measurement of knee valgus angles [31]. Although we have a standardized marker placement protocol and employed an experienced physiotherapist for this role, inconsistency of skin marker may still occur. Moreover, the jumping biomechanics could be affected by numerous factors such as an external encouragement [32] and training effect [33]. In the current study, the tester gave verbal encouragement to the subjects, however their regular team trainings were not controlled.

We were surprised to see a relatively large typical error of knee flexion angle and medial knee displacement during mid-stance in session 2 (figure 1). The observed variation was likely a result of variability of subject movement. A further analysis showed that the large typical error was generated by two subjects who performed jumps inconsistently, with both high and low knee flexion within the same session. When removing the two subjects from the analysis, the typical error waveform in session two was similar to session one (figure 3). Although it can be speculated that some jumps amongst the athletes with high variability should be excluded due to submaximal jumping performance, the jump heights were nearly identical. Hence, the jumps were correctly assessed to be valid trials according to our definition. Importantly, the knee valgus angles and internal rotation angles had a small and constant typical error throughout the whole stance phase in both sessions despite the variability in knee flexion.

The results obtained in this study are strikingly similar to those of Ford et al. [6]. With the exception of the internal rotation moments, the within and between session reliability for the two studies was close to identical (average ICC difference less than 0.1 for all common variables). In other words, the results of the two studies suggest that these findings may be valid across biomechanical laboratories using different protocols, and including different cohorts. Recent study of single-leg drop jumps have also showed good reliability between different labs [34]. However, it has been shown that different skin marker placement result in substantial changes in knee valgus measurement [31]. This highlights the necessity of standardized test protocols and experienced personnel.

An increase in typical error appeared in all the kinetic variables between 0 to 20% of the stance phase in all three directions (Figure 2). This is consistent to previous findings from Malfait and co-workers [7] who also concluded that kinetic measurement shortly after initial contact are more variable. The typical error was higher in the first phase due to the variability of the ground reaction force at around the impact [7]. However, they did not detect the mid-stance kinetics variation as found in the current study. The larger sample size (n =41) in our study may potentially explain the greater kinetic variability which was absent in the aforementioned study (n = 8).

Both ICC and Spearman's rank correlations observed for the various measures of lower limb biomechanics between the two sessions are generally satisfactory. This implies that the subject rankings could be reliably reproduced in multiple sessions. But from a screening perspective, the question is if repeated tests identify the same athletes as being at risk. Hewett et al. [1] have suggested that a high knee abduction (valgus) moment during a vertical drop jump task is a strong predictor for ACL injury risk. When using peak knee abduction moments (Spearman's rank correlation: 0.72), only 75% of athletes (nine out of 12) included in the top 30% in session one were also included in the top 30% in session two. However, the accuracy of lower limb biomechanics for identifying the risk of ACL injury needs to be established from a prospective cohort study using injuries as the outcome.

5. Conclusion

Our results suggest that biomechanical variables of the vertical drop jump task are reliable and can be used for research purposes. Additionally, the strong and positive between-session consistency of subject measurements and rankings imply that the ranking of athletes based on knee biomechanics in the vertical drop jump task can be reproduced reliably, which is critical for injury risk screening purposes. The vertical drop jump task can reliably measure knee valgus angles and internal rotation angles, which are believed to be related to the ACL injury mechanism. Furthermore, the new approach for calculating medial knee displacement was found to be reliable.

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