European Review for Medical and Pharmacological Sciences | 2022; 26: 7395-7403

Characteristics of vertical drop jump to screen the anterior cruciate ligament injury

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Abstract. – OBJECTIVE: To clarify the characteristics of vertical drop jump (VDJ) for screening athletes at high risk of ACL injury by comparing the kinematic, kinetic and electromyographic variables of different VDJ.

SUBJECTS AND METHODS: Thirty male soccer players were recruited to measure parameters of knee kinematics, kinetics, and surface electromyograph during VDJ in four kinds of movements measured (the distance between the take-off feet is 5 cm or 30 cm, and the distance between the landing feet is 5 cm or 30 cm) using the Vicon motion capture system, Kistler3-D dynamometer, and Noraxon surface electromyograph test system.

RESULTS: The peak knee abduction moment was significantly greater for landing feet distance of 30 cm compared to landing feet distance of 5 cm, regardless of whether the distance between take-off feet was 5 cm (0.58 *vs.* 0.44) or 30 cm (0.61 *vs.* 0.40); regardless of whether the distance between landing feet was 5 cm (22.78 *vs.* 20.45) or 30 cm (24.32 *vs.* 21.87), the peak vertical Ground Reaction Force was significantly increased for the take-off feet distance was 5 cm compared to take-off feet of 30 cm.

CONCLUSIONS: In the test of VDJ, athletes will adopt different landing strategies for different movement instructions, and the VDJ with the distance of 5 cm between the take-off feet and the distance of 30 cm between the landing feet may be the better maneuver to screen for risk of ACL injury.

Key Words:
Knee, Anterior cruciate ligament injury, Vertical drop jump, Screen risk.

Introduction

Anterior cruciate ligament (ACL) is an important stability structure of the knee, and its injury is one of the most common injuries to the knee. In football, the incidence of ACL injury is 0.06-3.7/1000 h[1] and the estimated incidence of ACL tear is 0.8%, and this number is higher in young athletes[2]. ACL injury can bring serious consequences to athletes, such as loss of exercise time, decreased athletic performance, and even termination of athletic career. Only 60% of patients with ACL injury can return to their pre-injury activity level after reconstruction, with the long-term consequences of early osteoarthritis[3]. These negative effects warn us of the importance of timely prevention of ACL injuries.

Studies[1,4] have shown that the number of non-contact ACL injuries in sports is significantly higher than contact injuries, which indicates that most ACL injuries are preventable. At present, prevention strategy for ACL injury is mainly through training interventions for neuromuscular control, balance and strength[5,6]. Petushek et al[7] reported that neuromuscular control training can reduce the risk of ACL injury and suggested that neuromuscular training for ACL injury prevention should be targeted at young athletes, with lower extremity strength training throughout the entire sports season, and special attention to landing training. Paulson et al[8] systematically reviewed ACL injury prevention methods and pointed out that reasons for inconsistent intervention effect of ACL injury prevention are various, training target for vulnerable people and injury-prone programs might be more effective. It is very important to determine the screening method for the vulnerable population of ACL injury. Screening out the vulnerable population and conducting targeted training for them is an efficient way to prevent ACL injury.

In 2005, Hewett et al[9] found for the first time that vertical drop jump (VDJ) test could be used to screen for the risk of ACL injury. They per-

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formed VDJ on 205 athletes: the results showed that athletes with larger knee valgus angle, abduction moment and higher ground reaction forces during the landing buffer phase had an increased risk of ACL injury. The knee abduction moment had sensitivity of 73% and specificity of 78% on predicting ACL injury, dynamic valgus measures showed a predictive of 0.88. However, some studies have shown that the VDJ test is a poor screening test for ACL injuries in athletes. Krosshaug et al[3] tested 710 elite athletes using VDJ and found that medial knee displacement was the only factor associated with increased ACL injury risk. A receiver operating characteristic curve analysis of medial knee displacement showed an area under the curve of 0.6, indicating a poor-to-failed combined sensitivity and specificity of the test, even when including previously injured players. Leppänen et al[10] proved that smaller knee flexion angle and larger vGRF during landing was associated with increased risk of ACL injury, but the areas under ROC curve were 0.6 and 0.7, respectively.

Based on the above argument, Augustsson et al[11] first paid attention to whether the specific characteristics of VDJ test affected the risk screening of ACL injury. They examined three VDJ tests: 1) stiff landing with the distance between the take-off feet is 30 cm and the distance between the landing feet is 30 cm (30 cm-30 cm), 2) deep "countermovement" jump with wide foot position (30 cm-30 cm) and 3) deep "countermovement" jump with narrow foot position (5 cm-5 cm). They found that compared to the stiff landing, there were greater knee valgus angles during landing for both deep "countermovement" jumps (30 cm-30 cm and 5 cm-5 cm). However, several previous studies[9,10,12,13] have confirmed that stiff landing with less knee flexion in a VDJ test was associated with increased risk of ACL injury. In addition, this study did not consider the different distance between the take-off feet and landing feet during a VDJ test (such as 5 cm-5 cm, 5 cm-30 cm, 30 cm-30 cm and 30 cm-5 cm). We think that a more detailed movement indication needs to be investigated to find out which VDJ is better to screen for ACL injuries and so far no study has explored different distance between the take-off feet and the landing feet about VDJ test.

Therefore, the purpose of this study was to clarify the influence of movement indication (the distance between the take-off feet is 5 cm or 30 cm, and the distance between the landing feet is 5 cm or 30 cm)[11] on knee kinematics, kinetics, and surface EMG around knee in male soccer players during VDJ and clarify the characteristics of VDJ can be used for ACL injury screening. Our hypothesis is as follows: the distance between the take-off feet is 5 cm and the distance between the landing feet is 30 cm of VDJ has the greatest knee abduction moment and is the most suitable for the screening of ACL injury.

Subjects and Methods

Study Design and Participants

Thirty-three male football players were recruited. The age of the subjects was 18.80 ± 1.08 y, the height was 174.70 ± 7.14 cm, the weight was 65.57 ± 7.82 kg, and the years of sports participation were 3.60± 1.97 y. G* Power software was used to calculate the sample size, and with an effect size of 0.25, significance of 0.05, and statistical power of 0.8 (Cohen effect size, weak 0.10, medium 0.25, large 0.40)[14], requiring at least 22 subjects. Inclusion criteria: university-level football players who exercise more than 3 times a week; there was no history of lower limb injury and joint degeneration within 3 months before the experiment; all subjects did not engage in strenuous exercise within 24 hours before the experiment. Exclusion criteria: subjects have a history of lower limb surgery, knee pain, lower limb neuromuscular dysfunction, or visible knee effusion. Approval for this study was obtained from the Institutional Review Board of Shandong First Medical University (ID number: 202103170147).

Experimental Process

Before the test, the subjects completed a 10 min warm-up. After the warm-up, the experimenter explained the basic requirements of the test and demonstrated the movements. The subjects were required to practice until they mastered the movements. During the experiment, the subjects wore the same tights. To reduce the differences during the test, the subjects wore unitive sports shoes. The subjects drop from a 34 cm wooden box which distance to force platforms is 30% of their height, with their feet at a certain distance (5 cm or 30 cm) and perform a maximal jump upon landing with their feet on 2 separate force platforms at a certain distance (5 cm or 30 cm), as shown in Figure 1. To reduce the difference in the experimental process, it is required that both hands placed on the waist during the landing process, and both hands do upward swing arm movements during the jumping[9,15]. If the above requirements are met, the data of three

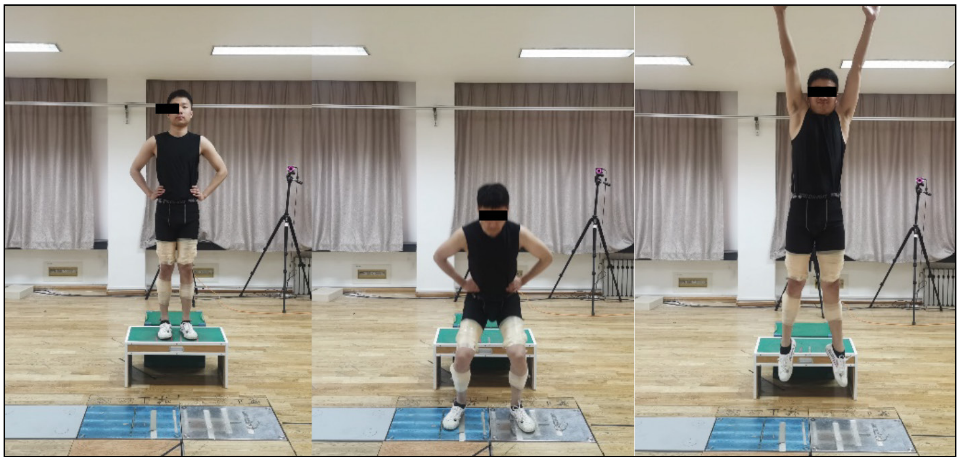

Figure 1. Vertical drop jump procedure.

experiments with successful measurement of each VDJ method were collected for analysis. To reduce the possible influence of learning effect on landing, the principle of digital random test was used for the four landing methods (5 cm-5 cm, 5 cm-30 cm, 30 cm-5 cm and 30 cm-30 cm).

Experimental Equipment and Data Processing

The experiment was conducted in biomechanics laboratory of the School of Sports Medicine and Rehabilitation, Shandong First Medical University. An optical motion capture system consisting of 8 infrared cameras was used (VICON, Oxford Metrics Limited, UK), and the acquisition frequency was 200 Hz. Sixteen reflective markers (diameter 14 mm) were pasted on the bony marks of the lower extremity of the subjects, including left and right anterior superior iliac spine, left and right posterior superior iliac spine, left and right lateral thighs, left and right lateral epicondyles of the knee, left and right lateral shanks, left and right lateral malleolus, left and right first metatarsal, and left and right heels. In addition, the kinematic analysis based on reflective markers was highly dependent on the placement of markers. To minimize inconsistency in marker placement, all marker locations were carefully defined, and a physical therapist was arranged to mark all subjects' markers. The acquisition frequency of two 60 cm×40 cm three-dimensional (3D) force platform (model 9286BA, KISTLER, Switzerland) was 1600 Hz. The 16-channel surface electromyography (EMG) test system (Desktop DTS, Noraxon, AZ, USA) was used to collect surface EMG signals from the muscles around the knee (vastus medialis, vastus lateralis, long head of biceps femoris, semitendinosus) at a frequency of 1500 Hz.

The main parameter of this study was knee abduction moment. Secondary parameters were flexion angle, valgus angle, vGRF and H/Q ratio. The landing phase of the VDJ was from the moment the foot touch the ground (vGRF > 10 N) to the peak flexion angle of the knee[16]. The kinematic data were smoothed by Butterworth low-pass filter with 6 Hz. The moment generated by knee joint was calculated by inverse dynamics after kinematic dynamic rigid body model was established. The EMG signal was processed by MR3 software, and the filtering frequency was 20 Hz for low frequency and 500 Hz for high frequency. Fourth-order full wave rectification without phase shift is adopted. The Windows was set to 50 ms, and the channel type was uniformly selected EMG and represented by Root Mean Square (RMS). Knee moments (Nm/kg) and vGRF (N/kg) were normalized by body weight. The maximum activity amount of each muscle during landing phase was normalized by the maximum activity amount during maximum voluntary isometric contraction (MVIC)[17]. The average muscle activity amount of vastus medialis and vastus lateralis was defined as muscle activity amount of quadriceps femoris, and the average muscle activity of long head and semitendinosus of biceps femoris was defined as muscle activity amount of hamstring muscle. H/Q ratio was defined as hamstring muscle activity amount/quadriceps muscle activity amount[18].

Table I. The effect of motion instruction on biomechanical variables of knee during VDJ.

	5-5	5-30	30-5	30-30
Peak flexion angle (°)	81.53 ± 5.84	83.41 ± 3.50	80.56 ± 4.59	81.92 ± 3.81
Flexion angle at IC (°)	19.29 ± 7.21	19.02 ± 7.35	17.69 ± 7.07	17.96 ± 6.55
Peak valgus angle (°)	6.42 ± 3.56	6.04 ± 4.44	5.13 ± 3.13	7.19 ± 3.32
Peak abduction moment (NM/kg)	0.40 ± 0.24	0.61 ± 0.35*	0.44 ± 0.29	0.58 ± 0.39*
Peak vGRF (N/kg)	22.78 ± 6.33#	24.32 ± 4.61#	20.45 ± 4.63	21.87 ± 3.60
quadriceps (%)	298.00 ± 49.30	302.15 ± 62.78	298.12 ± 62.53	291.84 ± 82.19
Hamstring (%)	182.44 ± 43.54	169.87 ± 46.14	179.32 ± 46.46	172.76 ± 55.18
H/Q	0.62 ± 0.14	0.60 ± 0.33	0.62 ± 0.17	0.62 ± 0.20

5-5 cm: The distance between the take-off feet is 5 cm and the distance between the landing feet is 5 cm; 5-30 cm: The distance between take-off feet is 5 cm and the distance between landing feet is 30 cm; 30-5 cm: The distance between take-off feet is 30 cm and the distance between landing feet is 5 cm; 30-30 cm: The distance between take-off feet is 30 cm and the distance between landing feet is 30 cm.IC: initial contact; vGRF: vertical Ground Reaction Force; * When the main effect is significant, post-test 5-30 *vs.* 5-5 and 30-30 *vs.* 30-5, $p < 0.05$; # When the main effect was significant, post-test 30-5 *vs.* 5-5 and 30-30 *vs.* 5-30, $p < 0.05$.

Statistical Analysis

Microsoft Excel 2010 and PRISM 8.0 statistical software were used to process and analyze all experimental data, which were expressed as mean ± standard deviation. Before statistical analysis, the data were tested for normal distribution using the one-sample k-s test, and the data in each group followed the normal distribution and the homogeneity of variance was the premise. Single-factor repeated measurement variance analysis was used to explore the effects of the distance between take-off feet and landing feet on the kinematics and kinetics and EMG parameters of the knee during the landing stage of VDJ, and pairwise comparison was performed using the post-Tukey test. If the normal distribution was not followed, Friedman test was used to compare the knee kinematics, kinetics, and EMG parameters during the landing stage of the four landing methods. The test level was $p = 0.05$.

Results

Friedman's test found that there was a significant difference in the peak knee abduction moment in the four landing movements ($p < 0.001$). The comparison between the groups showed that when the distance between the take-off feet was 5 cm, the peak abduction moment during VDJ with the landing feet distance of 30cm was significantly higher ($p < 0.05$). When the distance between take-off feet was 30 cm, the peak knee abduction moment during VDJ with the landing feet distance of 30 cm increased significantly ($p < 0.05$). There were no significant differences in peak knee flexion angle, peak knee valgus angle, vGRF and H/Q ratio ($p > 0.05$) (Table I and Figure 2).

The results of one-way repeated measure ANOVA analysis showed that the vGRF of the four landing movements had significant difference ($p < 0.05$). When the distance between landing feet was 5 cm, the vGRF was significantly increased ($p < 0.05$) during VDJ with the take-off feet distance of 5 cm. When the landing feet distance was 30 cm, the vGRF increased significantly during VDJ with the take-off feet distance of 5 cm ($p < 0.05$). There were no significant differences in peak knee flexion angle, peak knee valgus angle, peak knee abduction moment and H/Q ratio ($p > 0.05$) (Table I and Figure 3).

Figure 2 shows the temporary changes of knee abduction moment during landing phase of different VDJ. The result showed that the knee abduction moment of the four kinds of VDJs reach the peak value at ap-proximately 16.68% of the landing stage. The knee adduction moment reached its peak value at ap-proximately 89.02% of the landing stage of four kinds of VDJs.

Figure 3 shows the temporary changes of vGRF during landing phase of different VDJs. The result showed that the vGRF reaches the peak value at approximately 42.83% of landing phase of VDJ with the take-off feet distance of 5 cm and landing feet distance of 5 cm (5-5). The vGRF of the other three kinds of VDJ (5-30, 30-5 and 30-30) reached the peak value at approximately 46.39% of the landing stage.

Discussion

VDJ is a commonly used test to assess neuromuscular control and knee load, and has been widely used to screen the risk of ACL injury in

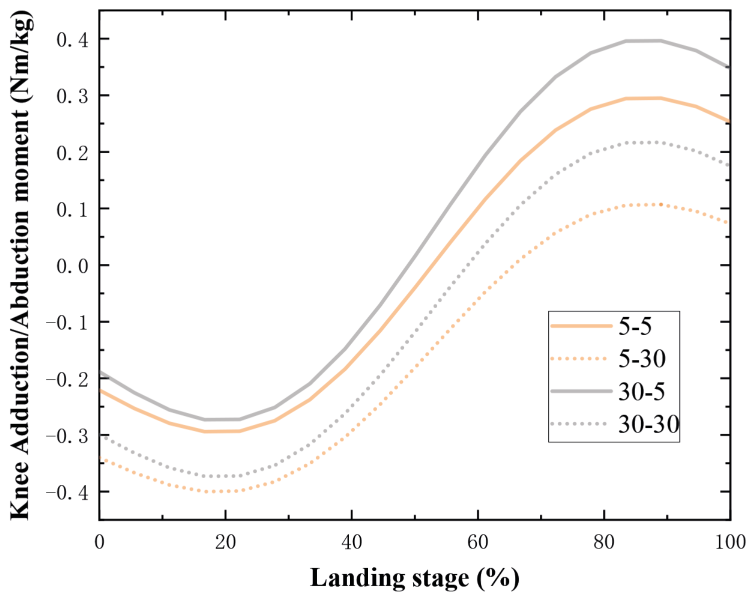

Figure 2. The temporary changes of knee adduction/abduction moment during landing phase of different VDJs.

athletes[9,19,20]. The purpose of this study was to clarify the influence of motion indication (distance between take-off feet 5 cm or 30 cm, distance between landing feet 5 cm or 30 cm) on the knee kinematics and kinetic and myographic parameters during landing phase of VDJ, and to clarify the characteristics of VDJ for ACL injury screening. For the first time, this study found that VDJ with the take-off feet distance of 5 cm and the landing feet distance of 30 cm has greater knee vGRF and peak valgus moment, may better screen ACL injury risk. This is the first recommendation for ACL injury risk screening using this kind of VDJ, which provides a theoretical basis for the development of appropriate ACL injury risk screening programs around the world. Coaches can carry out effective prevention and special intervention to athletes according to this screening program, to reduce the high ACL injury rate and high treatment costs of athletes.

In this study, no matter the distance of take-off feet was 5 cm or 30 cm, the knee abduction moment during landing phase of VDJ with the landing feet distance of 30 cm was significantly higher. Studies have shown that knee abduction moment can be used as a predictor of ACL injury with specificity of 73% and sensitivity of 78%[9]. Donohue et al[21] explored whether the single-leg landing, single-leg squat, double-leg landing, and double-leg squat could be used as ACL injury screening test, found that knee abduction moment during double-leg landing was greater than single-leg landing. When conducting the landing test and the VDJ test, Ishida et al[22] found that the latter significantly increased the peak knee abduction moment. In the current study, the peak abduction moment is larger during the landing phase of VDJ with landing feet distance of 30 cm, suggesting that VDJ with landing feet distance of 30 cm may better predict ACL injury risk. Therefore, it is recommended to screen for ACL injury. When the distance between the landing feet was 30 cm, the increase of the dynamic abduction moment of the knee might be caused by insufficient muscle contraction to resist the load generated by the abduction moment of the knee at the initial touchdown, resulting in the increase of the valgus loading, thus increasing the loading of the athlete's ligament structure[23,24]. In addition, scholars[25] have reported that the knee abduction moment may be related to different quadriceps and hamstring activation modes. However, in the current study, no significant differences were found in hamstring muscle activity, quadriceps muscle activity and H/Q ratio. Augustsson et al[11] also found no significant difference in activity of quadriceps muscle during VDJ with different landing depths. Therefore, further research is needed to determine whether muscle activity around knee during VDJ can be important risk factor of ACL injury. In this study, no

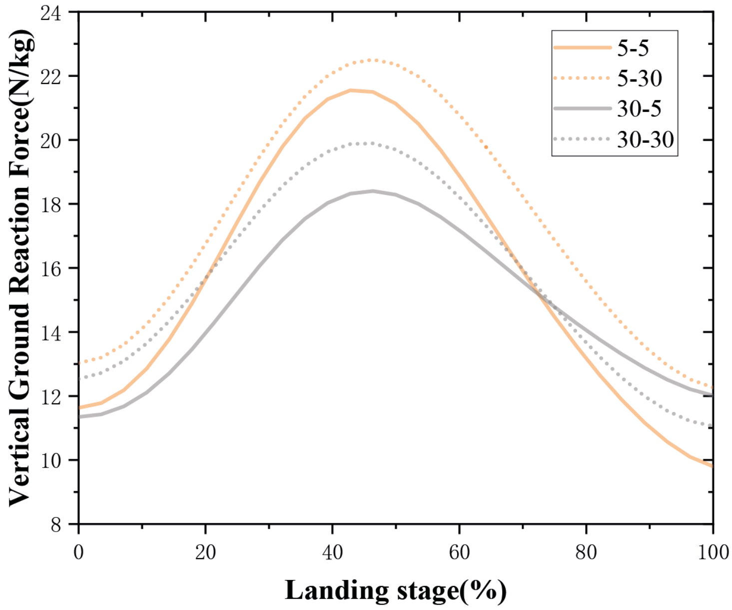

Figure 3. The temporary changes of vGRF during landing phase of different VDJs.

difference was found on knee peak valgus angle. Scholars[3] have confirmed that valgus angle, as a predictor of ACL injury risk, has low sensitivity and specificity, which may be the main reason for no difference. In addition, this study found no significant difference on the knee flexion angle and vGRF but found that the knee flexion angle at IC remained small. Myers et al[13] pointed out that a stiff landing with small knee flexion angle would increase the risk of ACL injury, but the area under the ROC curve was only 0.6, so the accuracy of screening ACL injury with flexion angle was poor. Similar to previous studies[26,27], this study also found that the knee abduction moment was the largest at 20% of the landing stage among the four kinds of VDJ, which was most likely to lead to ACL injury.

In this study, regardless of the distance between landing feet is 5 cm or 30 cm, the peak vGRF was significantly higher during the landing phase of VDJ with take-off feet distance of 5 cm. It has been reported that the identification of biomechanical features of risk of lower limb injury is usually done by assessing landing movements, as this task has been shown to induce higher vGRF and high-risk movement patterns[28]. This study firstly aims to discuss the influence of the distance between take-off feet on vGRF during VDJ. When the distance between take-off feet is 5 cm, it may not be conducive to absorbing the impact force of the ground and the vGRF increases during landing buffer, as well as the synchronization of peak vGRF and peak ACL stress during landing, thus increasing the stress on ACL[29,30]. Leppänen et al[31] conducted a VDJ test on 171 basketball players and found that vGRF was higher and knee flexion angle was lower in injured athletes. Similar studies also found that vGRF maintained a high value in both the double-leg landing screening task and the single-leg landing screening task[27,32]. However, although Leppänen et al[10] confirmed that a larger vGRF was associated with a higher risk of ACL injury in their study, the area under ROC curve was only 0.7, which lacked accuracy as a screening factor for the risk of ACL injury. Therefore, further research is needed to determine whether take-off feet distance of 5 cm is more conducive to the screening of ACL injury risk. In this study, no significant difference was found on the abduction moment of knee during landing phase of VDJ with different take-off feet distance. Leppänen et al[10] also found that vGRF had no significant correlation with the knee abduction moment and pointed out that vGRF was significantly correlated with knee flexion angle at initial contact and the stiff landing with less flexion angle at initial contact predisposed to produce larger vGRF. In this study, no significant difference was found in knee flexion angle at initial contact during landing phase of VDJ with the different take-off feet distance. However, it was found that all the stiff landing with a small knee flexion angle at IC. Similar to the results obtained with different landing feet distance, this study did not find significant differences on knee valgus angle and H/Q ratio during landing phase of VDJ with different take-off feet distances. In this study, vGRF of the four kinds of VDJ reaches its peak value at approximately 45% of the landing stage, which is similar to the conclusion of previous studies[33].

This study was completed in a laboratory under strictly controlled condition. Although high-risk VDJ movements on the playground have been simulated as far as possible, the environment and field still differ from the actual conditions on the real sports field. This study was based on the relevant kinematic, kinetic and myographic variables that lead to high risk of ACL injury determined by previous ACL injury screening studies and did not follow up on ACL injury after VDJ screening test under movement instructions, which is also the direction of our subsequent research. Since this study only compared male university-level football players, the results may not be directly applicable in female, other level, or specialized athletes. It is suggested that female and subjects of different sport types or level may be included in subsequent studies.

Conclusions

The test of VDJ with take-off feet distance of 5 cm and landing feet distance of 30 cm may be the better to screen ACL injury risk. This study provides a theoretical basis for ACL injury screening.

Conflict of Interests

The authors declare that they have no conflict of interests.

Funding

This work was supported by the National Natural Science Foundation of China (Grant No. 81472143), Shandong key R & D Program Project, China (Grant No. 2019GSF108203) and Project of Shandong Pharmaceutical Health Science and Technology Development Program, China (Grant No. 202020010808).

Authors' Contribution

B. Ma and T.-T. Zhang were the first authors in this paper; they conducted the screening for articles, conducted the data gathering, wrote the paper and edited the paper. Y.-D. Jia conducted statistical analysis of the paper, helped to write the paper, edited the paper and provided expertise on the subject matter. H. Wang and X.-Y. Zhu conducted the search for articles for the paper. W.-J. Zhang edited the paper and provided expertise on the subject matter. X.-M. Li and H.-B. Liu initiated the paper topic, edited the paper, and provided expertise on the subject matter. D. Xie was the principal investigator on this paper; he guided the drafting of the paper. All authors have read and approved the final submitted manuscript.

Ethical Approval

Approval for this study was obtained from the institutional review board of Shandong First Medical University (ID number: 202103170147).

Data Availability Statement

All data relevant to the study are included in the article or uploaded as supplementary information.

Informed Consent Form

All subjects volunteered to participate in the study and provided informed consent to participate.

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