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Research article

Potential for non-contact ACL injury between step-close-jump and hop-jump tasks

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Abstract
This study aimed to compare the kinematics and kinetics during the landing of hop-jump and step-close-jump movements in order to provide further inferring that the potential risk of ACL injuries. Eleven elite male volleyball players were recruited to perform hop-jump and step-close-jump tasks. Lower extremity kinematics and ground reaction forces during landing in stop-jump tasks were recorded. Lower extremity kinetics was calculated by using an inverse dynamic process. Step-close-jump tasks demonstrated smaller peak proximal tibia anterior shear forces during the landing phase. In step-close-jump tasks, increasing hip joint angular velocity during initial foot-ground contact decreased peak posterior ground reaction force during the landing phase, which theoretically could reduce the risk of ACL injury.

Key words: Stop-jump, inverse dynamics, shear force.

Introduction

The stop-jump is a frequently performed task in sports. The rate of anterior cruciate ligament (ACL) injury during stop-jump tasks is high (Renstrom et al., 2008). In forward stop-jump tasks, the relationship between ACL injury and sagittal plane mechanics during the landing phase has been well documented (Chappell et al., 2002; 2007; Sell et al., 2007; Yu et al., 2006). Yu and Garrett (2007) reported that non-contact ACL injuries occur when an anterior shear force generates large forces at the proximal tibia, leading to excessive tension force on ACL. A cadaveric study found that quadriceps and hamstring forces are the major contributors to anterior shear force at the proximal end of the tibia (DeMorat et al., 2004; Markolf et al., 1995; Withrow et al., 2006; 2008). Past research on the biomechanics of landing has shown that proximal tibia anterior shear force may be an indicator of anterior shear force at the proximal end of the tibia, and that the knee joint resultant moment may be an indicator of the resultant quadriceps and hamstring contraction forces (Chappell et al., 2002; Sell et al., 2007; Yu et al., 2006). Chappell et al. (2007) found that a stop-jump landing with increased quadriceps activation assists in increasing peak knee extension moment. Increasing peak knee extension moment has been shown to increase the peak proximal tibia anterior shear force (Chappell et al., 2002; 2007; Sell et al., 2007; Yu et al., 2006).

Previous studies have demonstrated a significant relationship between peak ground reaction forces (GRF) and knee injury (Hewett et al., 2005; Williams et al., 2004), particularly to ACL loading (Radin et al., 1991; Shelburne et al., 2004). Chappell et al. (2007) indicated that preparing for landing with increased hip and knee flexion may reduce ACL loading during a stop-jump landing. Yu et al. (2006) reported that decreasing hip and knee flexion during initial foot-ground contact increased the peak anterior shear force on the proximal tibia by increasing the peak ground reaction force during landing in a stop-jump task. Yu et al. (2006) showed that an increased hip and knee flexion angular velocity at initial foot-ground contact decreases peak GRF and peak proximal tibia anterior shear force during landing. The peak posterior GRF during a stop-jump landing is a very important component of the peak proximal tibia anterior shear force. Increasing the knee extension moment by increasing quadriceps muscle activity assists in counteracting the increased knee flexion moment that is created by the larger posterior GRFs experienced during landing (Yu et al., 2006; Yu and Garrett, 2007). Yu et al. (2006) reported that increasing active hip flexion motion during initial foot-ground contact decreases the peak proximal tibia anterior shear force by decreasing the peak posterior GRF.

Previous investigations are consistent in demonstrating the relationship between kinematics and kinetics: the motion of the hip and knee in the sagittal plane affect lower extremity loading (Chappell et al., 2002; Sell et al., 2007; Yu et al., 2006; Yu and Garrett, 2007). Unfortunately, these previous studies only focused on the hop-jump task for a two-footed landing followed by a two-footed take-off. The step-close-jump is also frequently performed in volleyball and basketball, with the primary difference between hop-jump and step-close-jump being the technique applied during the landing phase (Coutts, 1982). Whether the different landing techniques used in two stop-jump tasks affect lower extremity loading still not clear. Thus, the purpose of this study was to compare the kinematics and kinetics of the hop-jump and step-close-jump during landing and to provide further perspective on non-contact ACL injuries. We hypothesized (1) that there would be significant differences in the kinematics of two stop-jump tasks during landing and (2) that there would be significant differences in the kinetics of two stop-jump tasks during landing.

Methods

Participants

Eleven elite male, national university volleyball players

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without lower extremity injuries during the six months prior to the experiment were recruited as subjects for this study. The mean age, standing height, and body weight of subjects were 19.1 ± 3.3 years, 1.84 ± 0.04 m, and 79.6 ± 11.1 kg. Before the experiment, all subjects were informed of the methods and processes of the study, and a signed consent form was obtained. All subjects were blinded to the purpose of this study.

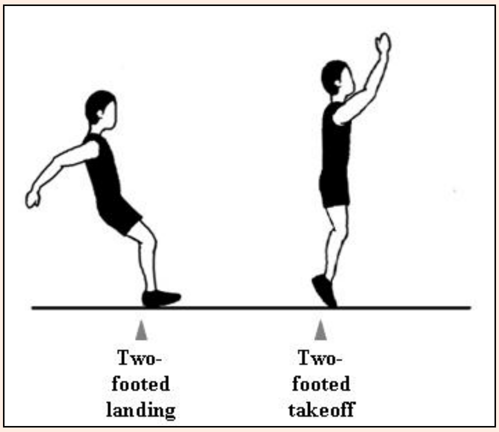

Figure 1. Hop-jump task.

Stop-jump tasks

Two volleyball stop-jump tasks were completed by asking the subjects to perform hop-jumps and step-close-jumps with great efforts. The maximum approach run speed permitted was with three steps followed by a stop-jump task. The hop-jump task consisted of a symmetrical two-footed landing and a two-footed takeoff for maximum height (Figure 1), while the step-close-jump task consisted of a lead leg landing ahead followed by a trail leg landing and a two-footed takeoff for maximum height (Figure 2).

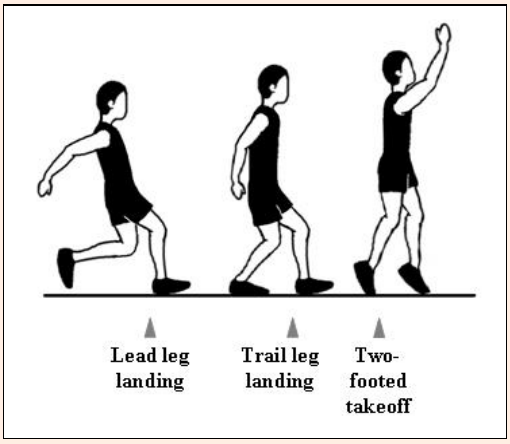

Figure 2. Step-close-jump task.

Data collection

Subjects were instructed to warm-up for 20 minutes and practice the stop-jump tasks before data collection. The order in which the two stop-jump tasks were performed was counterbalanced, and one day of rest was provided between tasks. Five successful performances for each stop-jump task were collected. The highest jumping performance for each stop-jump task was analyzed. The jumping height was calculated by the time of flight phase based on the GRF graph.

A Mega-Speed high speed camera was used to capture subjects' movement in the sagittal plane at 120 Hz. A 150×150 cm^2 calibration was used for direct linear transformation. Sixteen markers were placed on the right and left superior aspects of the scapular acromion process, styloid process of ulna, ulnar styloid, proximal interphalangeal joint of the third finger, greater trochanter, later condyle of the tibia, lateral maleolus, and fifth metatarsal according to Dempsters' segment parameters (Winter, 2005).

An AMTI force plate was used to record the raw analog data at a sampling rate of 1200 Hz. The force plate and high speed camera were time-synchronized using a Mega-Speed event synchronization unit. A reflective marker placed on the edge of the force plate was used register translational movement. Subjects were instructed to perform a step-close-jump such that only the lead leg was in contact with the force plate. However the subjects were instructed to land with two feet on the force plate together during landing of the hop-jump.

Data reduction

The marker trajectory data were measured and calculated using a Kwon3D motion analysis system and were low-pass filtered with a fourth-order Butterworth filter at cut-off frequency of 5 Hz. All kinematic calculations were performed in the Kwon3D software package. Raw analog data from the force plate were used to calculate the GRF, moments, and center of press position by using a KwonGRF system and were filtered with a fourth-order Butterworth filter at a cutoff frequency of 5 Hz. The origin coordinates of the motion analysis system were translated to the origin of the force plate's local coordinate system. A Newton-Euler inverse dynamic process was used to calculate the net joint reaction forces and net joint moments for the knee (Bresler and Frankel, 1950) using MATLAB. Body segment parameters were estimated from the marker data and Dempster's coefficients. All kinetic data were normalized to body weight.

The definitions of kinematics and kinetics parameters are shown in Figure 3. The hip joint angle was defined as relative angle of the thigh segment to the trunk segment. The knee joint angle was defined as the relative angle of the thigh segment to the shank segment. The jump height was calculated from the time of flight phase based on the GRF data, and was normalized to subjects' height. The initial time of landing of the two stop-jump tasks was defined as the time of initial foot contact with the ground after the approach run. The landing phase of two stop-jump tasks was defined as the interval between the initial time of landing and the minimum knee angle. The loading rate of the two stop-jump tasks was defined as the force-to-time ratio, where the force is the peak vertical GRF during the landing phase and the time is the interval between the initial time of landing to the peak vertical GRF during the landing phase (Winter, 2005).

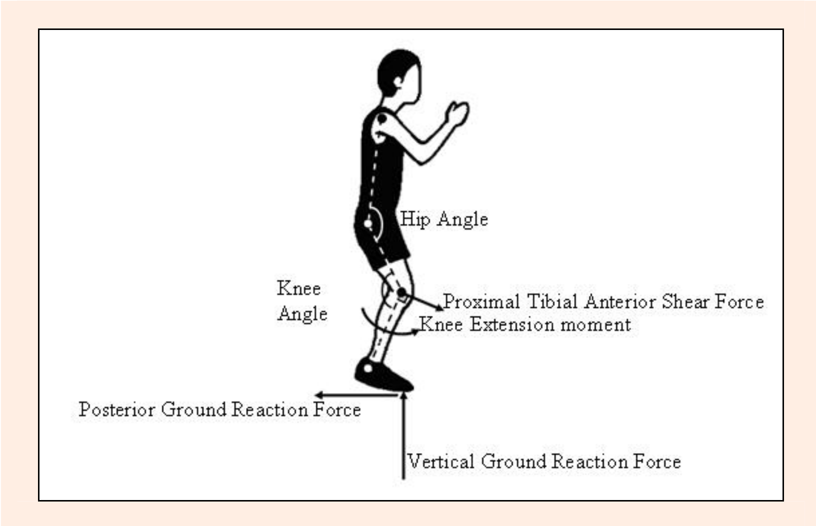

Figure 3. Kinematics and kinetics definition on the landing leg in the sagittal plane.

Data analysis

The data were analyzed using the Statistical Program for Social Sciences 14.0 for Windows package program. Analyses of variance were executed to compare jumping height, hip and knee angles and angular velocities at initial foot contact with the ground, minimum hip and knee angle, hip and knee angular displacement, peak GRF, time to peak vertical GRF, loading rate, peak knee extension moment, and peak proximal tibia anterior shear force during landing between the two stop-jump tasks. The mean and standard deviation were calculated for all variables. All data were analyzed using the dependent *t*-test to evaluate whether the means of the test variable differed significantly between the two stop-jump tasks. The significance level was set at $\alpha = 0.05$.

Results

Means and standard deviations for each dependent kinematic variable are presented in Table 1. There was no significant difference in jumping height between the step-close-jump and hop-jump ($p > 0.05$). The step-close-jump had a significantly larger hip and knee angle upon initial foot contact with the ground ($p < 0.05$), a significantly larger hip and knee angular flexion displacement during landing ($p < 0.05$), and a larger hip flexion angular velocity upon initial foot-ground contact in comparison to hop-jump ($p < 0.05$). There was no significant difference in angular velocity at initial foot-ground contact between the two stop-jump tasks ($p > 0.05$).

Means and standard deviations for each dependent kinetics variable are presented in Table 2. The step-close-jump had significantly smaller peak posterior GRF, peak vertical loading rate, and peak proximal tibia anterior shear force during landing in comparison to the hop-jump ($p < 0.05$). The duration from initial foot-ground contact to the peak vertical GRF appeared was significantly longer in the step-close-jump in comparison to the hop-jump ($p < 0.05$). There was no significant difference in peak vertical GRF and peak knee extension moment during landing between the two stop-jump tasks ($p > 0.05$).

Discussion

The performance of the landing in a stop-jump task is important for overall jumping performance following landing and for the prevention of lower extremity injuries during landing (Yu et al., 2006). Our research shows that there is no significant difference in jumping height between the hop-jump and step-close-jump. The purpose of this study was to compare potential ACL loading between step-close-jump and hop-jump tasks. In the previous study, peak proximal tibia anterior shear force during the landing was the major contributor to ACL tear injury. Prior research has demonstrated that hip and knee kinematics in the sagittal plane during a stop-jump landing affect lower extremity loading. The landing maneuvers of the step-close-jump and hop-jump were notably different. It was hypothesized that there was a significant difference in hip and knee kinematics between the two different stop-jump tasks. Also, it was hypothesized that there was a significant difference in lower extremity kinetics between the two different stop-jump tasks. The results of this study support our hypothesis in that there were

Table 1. Comparison mean (±SD) of jumping height, and lower extremity kinematics between hop-jump and step-close-jump tasks.

	Hop-jump	Step-close-jump
Jumping height (m)	.32 (.04)	.32 (.04)
Hip angle at initial foot contact with ground (deg)	108.9 (3.9)	117.9 (6.2) ***
Knee angle at initial foot contact with ground (deg)	144.9 (6.7)	156.8 (3.7) ***
Hip angular displacement during landing (deg)	7.5 (6.7)	20.7 (5.8) ***
Knee angular displacement during landing (deg)	50.1 (8.2)	64.5 (8.5) ***
Hip angular velocity at initial foot contact with ground (deg/sec)	-2.08 (1.52)	-4.53 (2.61) **
Knee angular velocity at initial foot contact with ground (deg/sec)	-5.77 (. 94)	-5.07 (1.47)

** and *** denote $p < 0.01$ and 0.001 respectively

Table 2. Comparison mean (±SD) of GRF, loading rate, knee extension moment, and proximal tibia anterior shear force lower extremity during landing between hop-jump and step-close-jump tasks.

	Hop-jump	Step-close-jump
Peak posterior GRF during landing (BW)	-1.26 (.08)	-.71 (.15) ***
Peak vertical GRF during landing (BW)	1.85 (.23)	1.83 (.17)
Time at which peak vertical GRF occurred following initial foot contact the with ground (sec)	.07 (.03)	.10 (.03) *
Peak vertical loading rate (BW/sec)	38.3 (25.0)	19.1 (6.0) *
Peak knee extension moment during landing (Nm/BW)	.56 (.10)	.51 (.23)
Peak proximal tibia anterior shear force during landing (BW)	1.59 (.24)	1.02 (.11) ***

** and *** denote $p < 0.05$ and 0.001 respectively

significant differences in the hip angle, knee angle, and hip flexion angular velocity upon initial foot-ground contact between the two stop-jump tasks. There were also significant differences in hip and knee angular flexion displacement, peak posterior GRF, peak vertical loading rate, and peak proximal tibia anterior shear force during landing between the two stop-jump tasks. These results suggest that using a step-close-jump technique rather than a hop-jump activity may reduce ACL injury risk in athletes performing stop-jump tasks.

The anterior shear force at the proximal end of the tibia is the most direct loading mechanism of the ACL during a non-contact activity (Markolf et al., 1995). It is important to note that the proximal tibia anterior shear force in this study can be estimated through inverse dynamics as a resultant force provided by the forces transmitted by the ligaments, soft tissues, and bony contact forces. It can also be represented as a single joint constraint force (Kaufman et al., 1991a; 1991b; 1991c; Sell et al., 2007). Prior research suggests that proximal tibia anterior shear force may be an indicator of anterior shear force at the proximal end of the tibia and may be a potential risk factor for non-contact ACL injury (Chappell et al., 2007; Sell et al., 2007; Yu et al., 2006). Stop-close-jump tasks in the current study displayed lower proximal tibia anterior shear forces than hop-jumps during landing. Based upon this result, we infer that the risk of ACL injury of a stop-jump task is lower in stop-close-jump techniques.

Landing with a lower peak posterior GRF may assist in reducing ACL loading. The peak posterior GRF during the landing of a stop jump may have the significant effect of lowering the proximal tibia anterior shear force (Sell et al., 2007; Yu et al., 2006). The results of our study are consistent with prior studies showing increased peak proximal tibia anterior shear force of hop-jump during the landing phase and increased peak posterior GRF during the landing phase.

In addition, it appears that peak posterior GRF during the landing of the stop-jump task is more likely associated with active hip flexion motion at initial foot-ground contact. Our results show that the step-close-jump required greater hip flexion angular velocity at the initial foot-ground contact and had a smaller peak posterior GRF and smaller peak proximal tibia anterior shear force during landing compared with the hop-jump. Our results are consistent with the results of Yu et al. (2006), who demonstrated that increasing hip joint angular velocity at initial foot contact with the ground decreased peak posterior GRF and decreased peak proximal tibia anterior shear force during the landing of the stop-jump task. These results combined indicate that, compared to the hop-jump, the step-close-jump had a smaller peak posterior GRF and smaller peak proximal tibia anterior shear force during landing. This was likely due to the greater active hip flexion motion at the initial foot contact with the ground. This characteristic of step-close-jump techniques may reduce the risk of ACL injury.

In addition, the peak posterior GRF may affect the muscular moment at the knee. Recent studies indicated that increased knee extensor moment for balance as the posterior GRF increased, and that knee extensor moment are the major contributors to the anterior shear force that affects ACL loading (Chappell et al., 2007; DeMorat et al., 2004; Yu et al., 2006; Yu and Garrett, 2007; Withrow et al., 2006). However, this argument was not supported in our study. The current results demonstrate that the hop-jump showed greater peak posterior GRF during the landing in comparison to step-close-jump. In addition, we found no significant difference in the knee extensor moment between the two stop-jump techniques. This indicates that the knee extensor moment may not be responsible for the landing task difference (hop and step-close) in the ACL loading of subjects during stop-jump tasks. However, the results of previous studies found that female recreational athletes tend to have a greater quadriceps muscle activation and lower hamstring muscle activation than do male recreational athletes during landing, leading to the inference that the female athletes have a greater relative risk of non-contact ACL injury than do male athletes (Chappell et al., 2007; Malinzak et al., 2001). Chappell et al. (2002) also indicated that the knee extension moment is affected by the quadriceps-to-hamstring muscle force ratio. Hence, the muscle EMG activity should be studied further for better understanding of the difference in quadriceps and hamstring muscle activity in the two stop-jump tasks.

Landing with lower loading rates may also assist in reducing ACL loading. The impact on the lower extremity increases as the peak vertical GRF and loading rate increased (McNitt-Gray, 1991; Zhang et al., 2000; Williams et al., 2004). The results of previous studies showed that a greater vertical GRF and loading rate is associated with knee joint injury (Williams et al., 2004; Hewett et al., 2005), especially in ACL (Radin et al., 1991; Shelburne et al., 2004). Yu et al. (2006) indicated that increasing knee angular velocity al initial foot-ground contact decrease peak vertical GRF during the landing of the stop-jump task. Our results show that there was no significant difference in knee flexion angular velocity at initial foot-ground contact between the two stop-jump tasks and that there was no significant difference in peak vertical GRF during landing between the two stop-jump tasks. However, the duration from initial foot-ground contact to the peak vertical GRF appeared is shorter in hop-jump. According to these results, the loading rate is greater in the hop-jump compared to step-close-jump, increasing the potential risk of ACL injury.

The joint angular displacement during landing may primarily affect the loading rate. Landing with greater hip and knee flexion angular displacement may decrease ACL loading. McNitt-Gray (1993) indicated that subjects appeared to increase shock attenuation via hip and knee flexion and that angular displacement must increase during landing, while the landing impact increases as the drop height increases in order to reduce the risk of injury. Zatsiorsky and Prilutsky (1987), and Devita and Skelly (1992) also reported that increased joint angular displacement during landing would reduce the peak value of the GRF and delay the time of the peak GRF. Blackburn and Padua (2008) reported that an increase in hip and knee flexion is associated with reduced ACL injury risk during a drop landing task. Yu et al. (2006) also reported that the increase in the peak proximal tibia anterior shear force in female recreational athletes may due to less hip and knee flexion during landing. The results of our study are consistent with the above-mentioned studies in that the step-close-jump action increases hip and knee flexion angular displacement during landing to reduce the loading rate.

Recent studies indicate that the joint angle of the lower extremity during initial foot contact with the ground may also affect ACL loading, and that greater hip and knee angle at initial foot-ground contact would increase the impact GRF and ACL loading during landing (Decker et al., 2003; Yu et al., 2006). However, the results of our study did not support this argument. Our results demonstrate that the step-close-jump required a larger hip and knee angle upon initial foot contact with the ground. Nonetheless, there was no significant different in peak vertical GRF between the two stop-jump tasks, whereas there was a greater loading rate, peak posterior GRF, and peak proximal tibia anterior shear force in the hop-jump task. The recent studies by Yu et al. (2006) and Sell et al. (2007) also indicate that the hip and knee angle at initial foot contact with the ground did not affect the landing impact of a stop-jump task. Based on these results, we consider that hip and knee angle upon initial foot-ground contact may not be affected by the lower extremity load during the landing of a stop-jump task.

Conclusion

In summary, we infer that three potential reasons for the higher risk of ACL injury in the hop-jump task compared to the step-close-jump task were that hop-jump was: 1. increasing the peak proximal tibia anterior shear force during the landing phase; 2. decreasing the hip joint angular velocity at initial foot contact with ground, leading to an increased peak posterior GRF during the landing phase; 3. decreasing hip and knee joint angular flexion displacement during the landing, increasing the loading rate during the landing phase. To the contrary, the different landing techniques required for these two stop-jump tasks do not necessarily affect the jump height.

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Key points

- The different landing techniques required for these two stop-jump tasks do not necessarily affect the jump height.
- Hop-jump decreased the hip joint angular velocity at initial foot contact with ground, which could lead to an increasing peak posterior GRF during the landing phase.
- Hop-jump decreased hip and knee joint angular flexion displacement during the landing, which could increase the peak vertical loading rate during the landing phase.

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