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Research article

The lower extremity biomechanics of single- and double-leg stop-jump tasks

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Abstract
The anterior cruciate ligament (ACL) injury is a common occurrence in sports requiring stop-jump tasks. Single- and double-leg stop-jump techniques are frequently executed in sports. The higher risk of ACL injury in single-leg drop landing task compared to a double-leg drop landing task has been identified. However the injury bias between single- and double-leg landing techniques has not been investigated for stop-jump tasks. The purpose of this study was to determine the differences between single- and double-leg stop-jump tasks in knee kinetics that were influenced by the lower extremity kinematics during the landing phase. Ground reaction force, lower extremity kinematics, and knee kinetics data during the landing phase were obtained from 10 subjects performing single- and double-leg stop-jump tasks, using motion-capture system and force palates. Greater peak posterior and vertical ground reaction forces, and peak proximal tibia anterior and lateral shear forces ($p < 0.05$) during landing phase were observed of single-leg stop-jump. Single-leg stop-jump exhibited smaller hip and knee flexion angle, and knee flexion angular velocity at initial foot contact with the ground ($p < 0.05$). We found smaller peak hip and knee flexion angles ($p < 0.05$) during the landing phase of single-leg stop-jump. These results indicate that single-leg landing may have higher ACL injury risk than double-leg landing in stop-jump tasks that may be influenced by the lower extremity kinematics during the landing phase.

Key words: Anterior cruciate ligament, kinematics, kinetics, ground reaction force.

Introduction

The anterior cruciate ligament (ACL) injury is a common occurrence in volleyball, basketball, and handball (Ferretti et al., 1992; Griffin et al., 2000; Olsen et al., 2004; Renstrom et al., 2008). Single- and double-leg stop-jump techniques are frequently executed in these sports. Yu et al. (2006) indicated that the landing phase of stop-jump tasks presents a significant risk of injury to the lower extremities in general and to the ACL in particular. A number of reports have shown that most sports-related ACL injuries occur during non-contact situations that are characterized by landing, rapid deceleration, and sudden changes of direction (Boden et al., 2000; Griffin et al., 2000).

A cadaver study reported that ACL injuries usually occur due to excessive ligamentous tension when an anterior shear force is generated at the proximal tibia (Markolf et al., 1995) by a concentrated force from the quadriceps (DeMorat et al., 2004; Markolf et al., 1995; Withrow et al., 2006). Recent studies have indicated that ACL injury risk factors were associated with knee kinetics that can be calculated by the inverse dynamic method, such as the resultant joint force (proximal tibia anterior shear force) and joint moment (Chappell et al., 2007; Sell et al., 2007; Yu and Garrett, 2007; Yu et al., 2006). Sell et al. (2007) and Yu et al. (2006) demonstrated that the increased proximal tibia anterior shear force and knee flexion moment during landing in a stop-jump task increase the non-contact ACL injury risk.

Previous studies have reported that the incidence of lower extremity injuries may be associated with the magnitude of the ground reaction force during landing (De Wit et al., 1995; McNitt-Gray, 1991; Zhang et al., 2000). Recent investigators have attempted to evaluate the influence of the ground reaction force on the proximal tibia anterior shear force and knee flexion moment during the landing phase of stop-jump tasks. Several studies have indicated that during landing in stop-jump tasks, the proximal tibia anterior shear force and knee flexion moment were associated with the ground reaction force, especially with the posterior horizontal ground reaction force (Sell et al., 2007; Yu and Garrett, 2007; Yu et al., 2006). Current studies have attempted to evaluate the influence of lower extremity kinematics on the ground reaction force during the landing phase of stop-jump tasks. Blackburn and Padua (2008) and Yu et al. (2006) indicated that increasing the hip and knee flexion angle and decreasing the hip and knee flexion angular velocity at the time of initial foot contact with the ground increases the peak ground reaction force during landing. Altogether, the risk of ACL injury was associated with knee kinetics that was influenced by the lower extremity kinematics during the landing phase of stop-jump tasks.

Single-leg landing is a common technique in sports. A great deal of work has been conducted pertaining to the injury bias between single- and double-leg landing techniques during drop landing tasks. Previous work suggests that in a single-leg drop landing task, subjects land with a significantly larger ground reaction force, an increased knee valgus angle at initial contact, a decreased peak knee flexion angle, and a decreased knee flexion angle and angular velocity at initial contact compared to a double-leg drop landing task (Pappas et al., 2007; Yeow et al., 2010). Unfortunately, the injury bias between single- and double-leg landing techniques has not been investigated for stop-jump tasks. These two stop-jump tasks are frequently performed in volleyball, basketball, and handball. It is important to determine whether similar differences occur in stop-jump tasks during landing. Therefore, the main purpose of this study was to determine the differences between single- and double-leg stop-jump tasks in hip and knee kinematics, knee kinetics,

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and ground reaction forces during landing. Based on previous studies, we hypothesized that, compared to the double-leg stop-jump, the single-leg stop-jump would (1) have smaller hip and knee flexion angles at the time of initial foot contact with the ground, (2) have lower hip and knee flexion angular velocities at the time of initial foot contact with the ground, (3) have a greater ground reaction force during landing, (4) have a greater knee joint reaction force during landing, and (5) have a greater knee flexion moment during landing.

Methods

Subjects

Ten elite male athletes, national university volleyball players between 19 and 27 years of age without lower extremity injuries during the six months prior to the experiment, were recruited as subjects for this study (Table 1). Each subject exercises for 1-2 h 3 times per week following a professionally designed training program. The mean age, standing height, and body weight of the subjects were 21.1 ± 2.2 years, 1.85 ± 0.04 m, and 80.7 ± 7.6 kg. Informed consent was obtained from all subjects prior to the experiment.

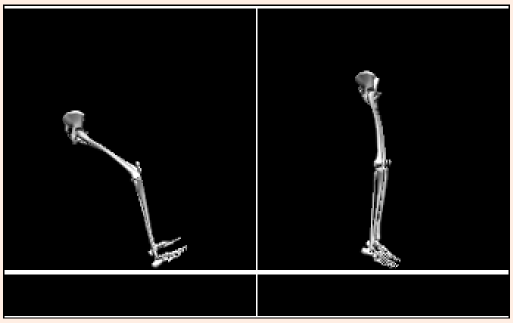

Figure 1. The double-leg stop-jump task consisted of three steps of approach run and a symmetric two-footed landing (left) followed by a two-footed takeoff symmetrically (right).

Data collection and reduction

The athletic tasks tested in this study were the single-leg stop-jump and double-leg stop-jump techniques frequently performed in volleyball, basketball, and handball. The maximum approach permitted was three steps followed by a stop-jump task with great effort. The double-leg stop-jump task consisted of a symmetric two-footed landing and a two-footed takeoff for maximum height (Figure 1). In volleyball, right-handed players perform the single-leg stop-jump task with the left leg, and all subjects in this study were right-handed. Therefore, the single-leg stop-jump task in this study consisted of a left leg landing and left leg takeoff for maximum height (Figure 2). The order of tests was randomized.

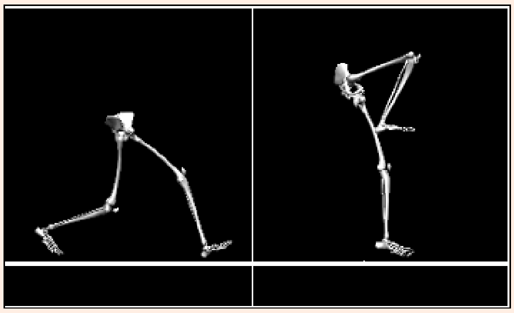

Figure 2. The single-leg stop-jump task for right-handed players consisted of three steps of approach run and a left-footed landing (left) followed by a left-footed takeoff (right).

Subjects were instructed to warm up for 20 minutes and practice the stop-jump tasks before data collection. The methods, processes, single-leg stop-jump task and double-leg stop-jump task of the study were described to the subjects. Each subject was asked to perform three successful trials of each stop-jump task. The subjects were asked to perform the stop-jump task as they naturally would for a spike in volleyball. Without an actual ball and a net, a string was hung above the front of the force plate in the ceiling. The string served as the target of the spike. The Qualisys Track Manager (QTM) motion capture and analog data acquisition system (Qualisys, Gothenburg, Sweden) with 6 infra-red Qualisys motion capture cameras (Oqus 100) and two AMTI force plates (BP600900, AMTI Inc., Watertown, MA, USA) was used to collect the three-dimensional coordinates of reflective markers on the subjects at 180 frames/s and the ground reaction forces during each trial at 1800 samples/channels/s. The trajectories of the reflective markers were synchronized in time with the collected force data by a Qualisys 64-channel A/D board. Data were collected with QTM software and imported into the MotionMonitor software (Innovative Sports Training, Inc., Chicago, IL, USA) for data reduction and analysis.

Twenty-one retro-reflective markers (19 mm in diameter) were attached to the lower extremities according to the Helen-Hayes Marker set. Retro-reflective markers were placed on the sacrum and bilaterally over the anterior superior iliac spine (ASIS), greater trochanter, thigh, lateral femoral epicondyle, medial femoral epicondyle, shank, lateral malleolus, medial malleolus, second metatarsal head, and posterior aspect of the heel. The hip joint center position was calculated using the retro-reflective markers attached to the ASIS (Bell et al., 1989).

Table 1. Means (standard deviations) of lower extremity kinematic variables during the landing of the single- and double-leg stop-jump tasks.

	Double-leg	Single-leg	*P*-value
Hip flexion angle at initial foot contact with ground (degree)	38.30 (9.02)	29.45 (9.26)	.002
Knee flexion angle at initial foot contact with ground (degree)	37.92 (12.32)	26.30 (6.53)	.019
Hip flexion angular velocity at initial foot contact with ground (degree/s)	78.50 (46.69)	-55.55 (57.33)	< .001
Knee flexion angular velocity at initial foot contact with ground (degree/s)	200.29 (63.33)	100.20 (64.82)	.004
Hip maximum flexion angle during landing (degree)	42.52 (8.44)	31.24 (8.52)	< .001
Knee maximum flexion angle during landing (degree)	84.74 (8.41)	57.50 (7.96)	< .001

The knee joint center position was defined as the mid-point between the lateral and medial femoral epicondyles. The ankle joint center position was defined as the mid-point between the lateral and medial malleolus. An inverse dynamic process was used to calculate the resulting joint forces and joint moments of the knee in each trial as described in previous studies (Sell et al., 2007; Yu et al., 2006). Figure 3 presents the definitions of the lower extremity kinetic parameters and ground reaction forces. All of the kinematic, ground reaction force, and inverse dynamics were calculated in the MotionMonitor software package. The 3-D coordinates of the markers during each stop-jump trial were filtered through a low-pass Butterworth digital filter at a cutoff frequency of 5 Hz (Sell et al., 2007). Raw analog data from the force plates were filtered through a low-pass Butterworth digital filter at a cutoff frequency of 50 Hz.

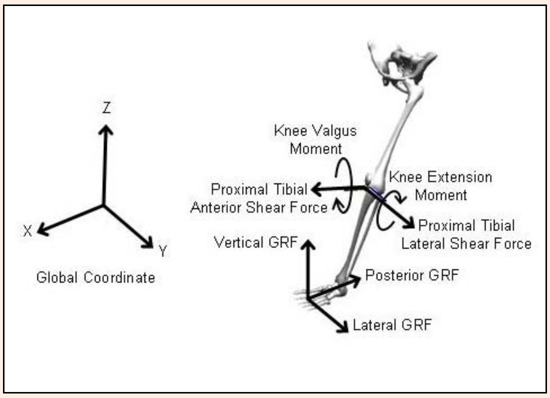

Figure 3. Kinetics definition on the landing leg.

The landing phase of the two stop-jump tasks was defined as the duration from the time of initial foot contact with the ground after the approach run to the time of maximum knee flexion. The ground reaction forces and resulting joint forces were normalized to body weight. The resultant joint moments were normalized to body weight*height. Kinematics and kinetic data were only collected from the left extremity for analysis. Data were averaged across three trials of each stop-jump task.

Statistical analysis

Statistical analysis was performed with SPSS (Statistical Package for the Social Sciences) 14.0 for Windows. The hip and knee flexion angles and flexion angular velocities at initial foot contact with the ground, maximum hip and knee flexion angles, peak posterior and vertical ground reaction forces, peak knee extension and valgus moments, and peak proximal tibia anterior and lateral shear forces during landing were compared between the two stop-jump tasks. Student's t-test was used to test for differences in dependent variables between the single-leg stop-jump and double-leg stop-jump tasks. The significance level was set at $\alpha = 0.05$.

Results

Table 1 presents the means and standard deviations of each dependent kinematic variable of the lower extremities. The single-leg stop-jump task had a significantly smaller hip and knee angle and a lower knee angular velocity at initial foot contact with the ground than the double-leg stop-jump task ($p < 0.05$). There was a significant difference in the hip flexion angular velocity at initial foot contact with ground between the two stop-jump tasks ($p < 0.05$). The double-leg stop-jump task tended to produce a hip flexion motion at the time of the initial foot contact with ground, whereas the single-leg stop-jump tended to exhibit a hip extension motion. The single-leg stop-jump had significantly smaller maximum hip and knee flexion angles during landing than the double-leg stop-jump ($p < 0.05$).

Table 2 presents the means and standard deviations of each dependent ground reaction force variable. The single-leg stop-jump task produced a significantly greater peak posterior ground reaction force and peak vertical ground reaction force during landing in comparison to the double-leg stop-jump task ($p < 0.05$).

Table 2. Means (standard deviations) of ground reaction forces during the landing of the single- and double-leg stop-jump tasks.

	Double-leg	Single-leg
Peak posterior ground reaction force during landing (BW)	.64 (.13)	1.15 (.27)*
Peak vertical ground reaction force during landing (BW)	1.96 (.25)	3.00 (.39)*

* $p < 0.001$

Table 3 presents the means and standard deviations of each dependent lower extremity kinetic variable. The single-leg stop-jump task produced a significantly greater peak knee extension moment and peak knee valgus moment during landing in comparison to the double-leg stop-jump task ($p < 0.05$). The single-leg stop-jump task also exhibited significantly greater peak knee proximal tibia anterior and lateral shear forces during landing than the double-leg stop-jump task ($p < 0.05$).

Table 3. Means (standard deviations) of lower extremity kinetic variables during the landing of the single- and double-leg stop-jump tasks.

	Double-leg	Single-leg
Peak knee extension moment during landing (BW * BH)	.17 (.03)	.20 (.06) †
Peak knee valgus moment during landing (BW * BH)	.12 (.04)	.27 (.08)*
Peak knee proximal tibia anterior shear force during landing (BW)	.59 (.08)	.80 (.15)*
Peak knee proximal tibia lateral shear force during landing (BW)	.27 (.12)	.59 (.23)‡

Discussion

The biomechanical characteristics of the landing in a stop-jump task are important to understand for the prevention of lower extremity injuries (Yu et al., 2006). The risk for non-contact ACL injuries in a single-leg landing is height (Olsen et al., 2004). Previous drop landing studies demonstrated that single-leg landings result in a greater risk of lower extremity injury than double-leg landings. Unfortunately, there is no similar understanding of the differences in injury mechanisms between single- and double-leg landings for stop-jump tasks, which are common in sports. The purpose of this study was to compare potential lower extremity loading between single- and double-leg landings during stop-jump tasks. In our investigation, the hypotheses that single-leg stop-jumps would have smaller hip and knee flexion angles and angular velocities at initial foot contact with the ground were accepted. Additionally, the hypotheses that the landing of a single-leg stop-jump would produce a greater ground reaction force, a greater knee joint reaction force, and a greater knee flexion moment were accepted. These results suggest that using a single-leg stop-jump technique rather than a double-leg stop-jump may increase the risk of lower extremity injury in athletes.

Previous studies indicated that the impact on the lower extremities increases as the peak vertical ground reaction force increases (McNitt-Gray, 1991; Radin et al., 1991; Shelburne et al., 2004; Williams et al., 2004; Zhang et al., 2000). Several previous studies have compared the ground reaction force between single-leg drop landings and double-leg drop landings (Pappas et al., 2007; Yeow et al., 2010). Pappas et al. (2007) found that single-leg drop landings from a height of 0.4 m produced a higher peak vertical ground reaction force than double-leg drop landings from the same height. Similarly, Yeow et al. (2010) demonstrated a higher peak ground reaction force for single-leg drop landings than for double-leg drop landings from heights of 0.3 m and 0.6 m. A similar phenomenon was found in stop-jump tasks, with the results of our study showing a greater peak vertical ground reaction force during the landing phase of single-leg stop-jumps than double-leg stop-jumps. Based on this result, we infer that the single-leg stop-jump may involve a greater risk of lower extremity injury than the double-leg stop-jump.

The knee kinematics during the landing phase are likely to be an important factor affecting the vertical ground reaction force. The increased vertical ground reaction force during landing is likely due to 1) decreased hip and knee flexion angles at initial foot contact with the ground (Decker et al., 2003; Yu et al., 2006), 2), decreased maximum hip and knee flexion angles during landing (Decker et al., 2003; Yu et al., 2006), and 3) a decreased knee flexion angular velocity at initial foot contact with the ground (Yu et al., 2006). Malinzak et al. (2001) and Yu et al. (2006) further indicated that a decreased knee flexion angle during landing may increase the loading on the ACL. As our results show, the single-leg stop-jump produced a greater vertical ground reaction force than the double-leg stop-jump, which was likely due to the smaller hip and knee flexion angles at initial foot contact with the ground, the smaller maximum hip and knee flexion angles during landing, and the smaller knee flexion angular velocity at the time of initial foot contact with the ground. The results obtained in the current study are consistent with those of previous studies examining the ground reaction forces and knee kinematics during single-leg and double-leg drop landings (Yeow et al., 2010).

Non-contact ACL tears occur due to excessive strain on the ACL (Yu and Garrett, 2007). The previously referenced cadaver study indicated that the anterior shear force acting on the proximal of the tibia is an important factor in ACL strain (Markolf et al., 1995). A number of studies have investigated ACL loading, with the proximal tibia anterior shear force estimated through inverse dynamics (Chappell et al., 2002; Sell et al., 2007; Wang et al., 2010; Yu et al., 2006). These studies illustrated that the proximal tibia anterior shear force may be an indicator of ACL loading. Our results show that the single-leg stop-jump produced a greater peak proximal tibia anterior shear force during the landing phase compared to the double-leg stop-jump. This indicated that non-contact ACL injuries may be more likely to occur during single-leg stop-jump tasks than during double-leg stop-jump tasks.

The knee extension moment is likely to be an important factor affecting the proximal tibia anterior shear force during the landing of a stop-jump task. Previous studies have reported that increased quadriceps muscle forces produce increased proximal tibia anterior shear forces (DeMorat et al., 2004; Markolf et al., 1995; Withrow et al., 2006), whereas increased hamstring muscle forces cause decreased proximal tibia anterior shear forces (Withrow et al., 2008). Chappell et al. (2002) indicated that increasing the quadriceps-hamstring muscle force ratio increased the knee extension moment estimated through inverse dynamics. A number of studies have investigated the relation of the proximal tibia anterior shear force with the knee extension moment (Chappell et al., 2002; Sell et al., 2007; Wang et al., 2010; Yu et al., 2006). Sell et al. (2007) demonstrated that the knee extension moment can be used to predict the proximal tibia anterior shear force during a stop-jump task. During stop-jump tasks, increased knee extension moments caused increased proximal tibia anterior shear forces (Chappell et al., 2002; Wang et al., 2010; Yu et al., 2006). Furthermore, strain on the ACL is more likely to occur with a greater valgus moment at the tibia (Bendjaballah et al., 1997). Our results show that the single-leg stop-jump produced a greater peak knee extension moment during the landing phase than the double-leg stop-jump. Our results further show that the single-leg stop jump exhibited a greater knee valgus moment and knee proximal tibia lateral shear force during landing than the double-leg stop jump. Taken together, these results indicate that the increased peak proximal tibia anterior shear force in the single-leg stop-jump task was likely due to the greater peak knee extension and valgus moment during landing.

The posterior ground reaction force during landing is likely to be an important factor affecting the knee extension moment during the landing of a stop-jump task. During landing, a flexion moment at the knee is created when a posterior ground reaction force appears and is counteracted by a quadriceps muscle force, thus resulting in a knee extension moment (Yu et al., 2006; Yu and Garrett, 2007). Recent research found that the peak posterior ground reaction force is positively correlated to the peak knee extension moment (Yu et al., 2006). Increased posterior ground reaction forces caused increased knee extension moments during the landing of the stop-jump task (Chappell, 2002; Yu et al., 2006; Wang et al., 2010). However, previous studies did not provide information on the differences between the posterior ground reaction forces in single- and double-leg landings. Our results show that the single-leg stop-jump produced a greater peak posterior ground reaction force during the landing phase than the double-leg stop-jump. This indicates that the greater peak knee extension moment in the single-leg stop-jump task was likely due to the greater posterior ground reaction force during landing.

The hip flexion angular velocity at initial foot contact with the ground is likely to be an important factor affecting the posterior ground reaction force. Yu et al. (2006) indicated that active hip flexion motions play an important role in the reduction of posterior ground reaction forces. Previous studies reported that increasing the hip flexion angular velocity at initial foot contact with the ground decreased the peak posterior ground reaction force during landing (Wang, et al., 2010; Yu et al., 2006). As the results of this study show, the single-leg stop-jump task tended to exhibit a hip extension movement at the time of initial foot contact with the ground, whereas the double-leg stop-jumps tended to feature a hip flexion movement. Furthermore, the results of this study show a greater peak posterior ground reaction force for single-leg stop-jumps than double-leg stop-jumps during the landing phase. Taken together, these results suggest that double-leg landing and single-leg landing stop jumps may involve different movement strategies. These differences in movement strategies between double-leg stop-jumps and single-leg stop-jumps may result in increased peak posterior ground reaction forces during the landing of single-leg stop-jumps than double-leg stop-jumps.

Variations in the speed and stride length in the last step of the approach run are the main limitations of this study. Subjects were instructed to perform a three-step approach with great effort. The approach speed was not restricted, and the stride length was not adjusted. These parameters could affect the magnitudes of the evaluated joint reaction forces and moments. In addition, we only investigated the sagittal plane kinematics of the landing of the stop-jump task. The effects of knee valgus-varus and internal-external angles on ACL loading should be considered in future studies to improve our understanding of the mechanisms and risk factors involved in non-contact ACL injuries.

Conclusion

In summary, there are significant differences between the landing phase kinetics of double- and single-leg stop-jumps. We infer that a higher risk of ACL injury in the single-leg stop-jump task could result from the fact that the single-leg stop-jump exhibited greater peak proximal tibia anterior and lateral shear forces during the landing phase than the double-leg stop-jump task. Moreover, increasing the proximal tibia shear force in the single-leg stop-jump task may result in the following: 1) decreased hip and knee flexion angles at initial foot contact with the ground; 2) a decreased knee flexion angular velocity at initial foot contact with the ground; 3) extension of the hip joint at initial foot contact with the ground; 4) decreased peak hip and knee flexion angles during the landing phase; 5) increased peak posterior and vertical ground reaction forces; and 6) increased peak knee extension and valgus moment.

Acknowledgments

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Key points

- Non-contact ACL injuries are more likely to occur during the single-leg stop-jump task than during the double-leg stop-jump task.
- Single-leg stop-jump exhibited greater peak proximal tibia anterior and lateral shear forces, and peak posterior and vertical ground reaction forces during the landing phase than the double-leg stop-jump task.
- Single-leg stop-jump exhibited smaller hip flexion angle, knee flexion angle, and knee flexion angular velocity at initial foot contact with the ground.
- Single-leg stop-jump exhibited greater peak knee extension and valgus moment during the landing phase than the double-leg stop-jump task.
- Single-leg stop-jump extended the hip joint at initial foot contact with the ground.

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