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Timing differences in the generation of ground reaction forces between the initial and secondary landing phases of the drop vertical jump ☆

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Abstract

Background—Rapid impulse loads imparted on the lower extremity from ground contact when landing from a jump may contribute to ACL injury prevalence in female athletes. The drop jump and drop landing tasks enacted in the first and second landings of drop vertical jumps, respectively, have been shown to elicit separate neuromechanical responses. We examined the first and second landings of a drop vertical jump for differences in landing phase duration, time to peak force, and rate of force development.

Methods—239 adolescent female basketball players completed drop vertical jumps from an initial height of 31 cm. In-ground force platforms and a three dimensional motion capture system recorded force and positional data for each trial.

Findings—Between the first and second landing, rate of force development experienced no change ($P > 0.62$), landing phase duration decreased ($P = 0.01$), and time to peak ground reaction

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force increased ($P < 0.01$). Side-by-side asymmetry in rate of force development was not present in either landing ($P > 0.12$).

Interpretation—The current results have important implications for the future assessment of ACL injury risk behaviors. Rate of force development remained unchanged between first and second landings from equivalent fall height, while time to peak reaction force increased during the second landing. Neither factor was dependent on the total time duration of landing phase, which decreased during the second landing. Shorter time to peak force may increase ligament strain and better represent the abrupt joint loading that is associated with ACL injury risk.

Keywords

Drop jump; ACL; Drop land; Ground reaction force; Rate of force development

1. Introduction

Large vertical ground reaction forces (vGRF) generated over a short time period (high impulse) are associated with increased ACL injury risk, as most non-contact injuries occur at high velocity (DeVita and Skelly, 1992; Olsen et al., 2004). Female athletes are known to display altered mechanics that are likely associated with their higher injury risk during jump landings than their male counterparts (Hewett et al., 2006; Hughes et al., 2010), this includes the rate of force development (RFD) (Quatman et al., 2006). Females have been documented to display increased RFD during landing compared to males (Prapavessis et al., 2003). These rapid impulse loads imparted on the lower extremity may contribute to greater ACL injury prevalence in female athletes.

The drop vertical jump (DVJ) is a dynamic movement that has frequently been used to identify biomechanical characteristics that contribute to ACL injury risk in athletic populations (Ford et al., 2011; Hewett et al., 2005; McNair and Prapavessis, 1999). DVJs mimic the rapid deceleration followed by maximal vertical jump observed in a rebounding task, which happens to be the task most commonly associated with ACL injury in basketball (Powell and Barber-Foss, 2000). The DVJ task consists of two landing phases; the first of which follows a drop off a stationary platform and precedes a maximal vertical jump, and the second of which follows the maximal vertical jump and completes the task. Thus, the first landing in a DVJ is a drop jump, whereas the second is a drop landing. Drop jumps and drop landings elicit different neuromechanical responses that dichotomize the tasks (Ambegaonkar et al., 2011; Shultz et al., 2012). Specifically, lower extremity muscles demonstrated greater peak activation magnitudes in drop jumps than drop landings, but time to peak activation remained equivalent between tasks. Apart from this, little to no work has evaluated the timing differences in force generation between a drop jump and drop landing. Therefore, the purpose of this study was to compare the landing phase duration, time to peak vGRF, and RFD in the first landing of a DVJ to those of the second landing. The hypothesis tested was that biomechanical events would occur at different times and the magnitude of RFD would change between landing phases.

2. Methods

Participants included in the current study were from a cohort in a prospective, longitudinal study. A population of 239 middle school ($n = 162$) and high school ($n = 77$) female basketball players (mass = 55.4 (13.2) kg, height = 1.60 (0.09) m, age = 13.6 (1.6) years) were tested immediately preceding their upcoming season. Procedures were approved by the institution's review board and informed written consent was obtained from each participant's parent or legal guardian. Participant consent was also obtained for each subject prior to testing.

Collection methods for this study were previously documented (Bates et al., 2013a). Briefly, each subject was instrumented with reflective markers and asked to perform three DVJs from a box height of 31 cm. Data was recorded from each DVJ with a 10-camera, 3D motion analysis system (Eagle cameras, Motion Analysis Corporation, Santa Rosa, CA) and dual, in-ground, multi-axis force platforms (AMTI, BP600900 Watertown, MA). Landing phase data was processed separately for the first and second landings in Visual3D (version 4.0, C-Motion, Inc., Germantown, MD) with custom Matlab (version 2010b, The Mathworks, Inc., Natick, MA) code. Each landing phase was defined as the point of initial contact with the force platforms through the lowest center of mass point recorded during stance. If participants failed to land with each footprint completely contained on separate force platforms during the second landing, the trial was excluded from analysis as vGRF data would be incomplete. RFD was calculated as the peak vGRF divided by the time from initial contact to peak vGRF (Decker et al., 2002). All references to timing were made relative to the point of initial contact during respective landings. For each subject, a mean of the successful three trials was calculated. For each subject, a mean of the successful three trials was calculated. Data from subject means was used in ANOVA and Student's t-tests to evaluate differences between landing phase and leg side. Statistical significance was established a priori at $P = 0.05$.

3. Results

Cumulative RFD was statistically unchanged in the second landing relative to the first ($P = 0.62$; Table 1). There was a significant landing-by-side interaction for RFD ($P = 0.01$). When separated individually, there was no statistical difference in RFD between landings for the left limb ($P = 0.70$) or right limb ($P = 0.19$), though the absolute RFD value for the right limb decreased by 3 N/ms from the first to second landing. Side-by-side asymmetry for RFD was not present in the first landing ($P = 0.12$), nor the second landing ($P = 0.76$), though the absolute RFD value was 3 N/ms greater in the right limb during the first landing.

The landing phase was 15% shorter in average total duration during the second landing as the center of mass reached its lowest point more rapidly following initial contact than in the first landing ($P < 0.01$; Fig. 1). The duration of the first landing phase averaged 0.20 (0.04) seconds in length starting from the time point at which initial contact with the force platform was recorded, while the second landing phase averaged 0.17 (0.04) seconds. The cumulative time from initial contact to peak vGRF was longer in the second landing, than the first ($P < 0.01$; Table 2). Between landings, the right leg exhibited a longer time to peak vGRF in the

second landing than in the first ($P < 0.01$); however, there was no between landing difference in the left leg ($P = 0.19$). Within landings, there were no side-to-side differences in time to peak vGRF ($P > 0.15$).

4. Discussion

The purpose of the current study was to compare the landing phase duration, time to peak vGRF, and RFD in the first landing of a DVJ to those of the second landing. RFD was consistent, but duration of landing phase and time to peak vGRF were not consistent between the two landings in a DVJ. RFD was observed to have no statistically significant differences between the first and second landings, which supported the null hypothesis that there would be no differences between landings. Previous research conducted on the same population cohort indicates that peak vGRF between the first and second landings of a DVJ are statistically constant (Bates et al., 2013a). Hence, participants in the current study encountered both a similar amount of impact force and cumulative RFD on both the first and second landings of the DVJ.

Though the differences in RFD between landing and between legs within landing expressed no statistically significant differences, it is worth noting that the absolute values of these measures were not identical. Between landings the right leg RFD decreased by approximately 3 N/ms from first to second landings, while within the first landing the right leg RFD was approximately 3 N/ms greater than the left leg. Relative to clinical outcome, if these RFD changes are extrapolated across the time to peak vGRF (0.062–0.072 s) they would result in peak vGRF differences in the range of 186–216 N. Again these RFD differences were found to be statistically insignificant and such forces would be dissipated across multiple structures within the knee joint, but it is worth noting that the force values account for up to 10% of the maximum linear tensile strength of the ACL, which has previously been reported as 2100 N in young, healthy knees (Woo et al., 1991). Therefore, it is possible that the increased RFD in the right limb during the first landing may have placed greater load and strain on the ACL; however, in vitro cadaveric studies or in situ computer simulations would be necessary to assess this possibility.

Despite statistical similarities in RFD, the right limb exhibited shorter time to peak vGRF during the first landing. The attainment of equivalent peak vGRFs over a shorter duration of time, even with statistically equivalent RFDs, is likely to increase the mechanical strain within a joint. Absorbing force over shorter time duration is a factor known to be associated with ACL injury risk (Hewett et al., 2005). It is possible that the right limb enacted a different neuromuscular pathway between landings that allowed participants to reach their peak vGRF faster in the first landing than the second landing. It was previously reported that the cohort used in this study exhibited no significant differences in peak center of mass height during flight prior to the first and second landings (125 cm and 124 cm, respectively) (Bates et al., 2013a). Therefore, biomechanical differences between landings can be attributed to participant response rather than external influences such as changes in fall height. Neuromuscular and biomechanical differences were reported between the first and second landings of a DVJ as well as between the drop jump and drop landing tasks they mimic, respectively (Ambegaonkar et al., 2011; Bates et al., 2013b; Shultz et al., 2012).

Decreased time to peak vGRF in the first landing, along with the statistically insignificant increase in RFD, may indicate that this landing phase exhibits mechanical behaviors that better represent joint loading that leads to injury than the second landing.

While the second landing phase was approximately 15% shorter in duration than the first landing phase, the RFD remained unchanged between landings. Hence, the overall time duration of landing phase may not be directly proportional to RFD. Similarly, time to peak vGRF is not dependent on the total duration of the landing phase. Differences in landing phase duration may be related to the presence of different landing mechanics during the first and second landings of the DVJ. Anticipation of subsequent task, such as the drop jump in the first landing as compared to the drop landing in the second landing, can lead to neuromechanical and functional differences in performance of a task (Ambegaonkar et al., 2011). Altered time to peak vGRF between landings of equal fall height that generate equal peak vGRFs may result from the separate muscle activation patterns documented in a drop jump and drop landing. Such differences may be related to neuromuscular control and predispose each landing of a DVJ to better screen for separate predictors related to ACL injury risk.

Changes in time to peak vGRF were also independent of the time duration of the landing phase. Whereas landing phase total duration decreased from first to second landings, cumulative time to peak vGRF increased slightly. However, though statistical differences were present in time to peak vGRF between landings, the magnitude of these differences may not be clinically relevant as the average difference between the first and second landings was 0.008 s. Though this value represents between 13 and 15% of the time to peak vGRF in both landings, it also represents less than 5% of the total duration of either landing phase and the clinical relevance of such a small deviation remains uncertain.

The left limbs experienced equivalent time to peak vGRF between landings; however, the right limb time to peak vGRF increased from first to second landing. Therefore, even though no side-to-side asymmetries were documented within each landing, there was asymmetry present as one limb experienced change between the first and second landings whereas the contralateral limb did not. Of this population, 93.3% of participants indicated their right limb to be preferred (preferred limb was determined by asking each athlete which leg they would use to kick a ball). Thus, the data indicates that athletes may have differences in neuromuscular control between their preferred and non-preferred limbs as only one side experienced change in time to peak vGRF between tasks (Ford et al., 2003; Hewett et al., 2005). Such relative changes in time to peak vGRF between landings in a DVJ may provide researchers with a unique mechanism for evaluation of leg dominance and side-to-side asymmetry in an athlete. As explicit technique instructions drew each participant to focus on body mechanics during the first landing and the suspended target subsequently diverted this attention in the second landing, it is possible that athletes naturally favor their preferred limb when concentrating on the mechanics of a landing task. It is known that female soccer athletes are significantly less likely to experience ACL injury in their preferred kicking leg than in the contralateral limb (Brophy et al., 2010). This raises a question as to whether the change in time to peak vGRF in the preferred limb between drop jump and jump landing tasks exhibits an underlying ability of the preferred limb to make neuromuscular adaptations

that may be absent in the non-preferred limb. Such adaptability could allow the preferred limb to optimize neuromuscular pathways to best shield itself from stresses generated by various tasks, whereas the non-preferred limb may consistently enact the same pathway regardless of task. Additional study would be required to investigate this possibility.

The current study shares identical data collection methods and population cohort with previous work and therefore a large number of trials were exempted by the exclusionary criteria outlined in our methodology. The relatively high prevalence of excluded trials may have artificially reduced the overall variability and significance demonstrated within this cohort (Bates et al., 2013a). A potential limitation unique to this study lies in the calculation of RFD. RFD was calculated as though there was a single, constant force slope from initial contact to peak vGRF. As indicated by Fig. 1, this was not the case. During landing, participants experienced a second, lesser vGRF spike prior to the maximal vGRF peak. Therefore, during force generation, there were actually two RFD slopes that were averaged into one value by the present calculations. Further work is necessary to identify whether these individual slopes associate with ACL injury risk.

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Fig. 1.

Depiction of the population mean vGRF curve, with one standard deviation, against time for each leg during the first and second landing phases of a DVJ. Forces are plotted from initial contact to lowest point of center of mass during contact.

Table 1

Displays the population mean RFD values (N/s) recorded for the right and left leg during the first and second landings of a DVJ.

	1st landing	2nd landing
Left	23,548	24,446
Right	26,533	23,639
Total	50,080	48,084

^aIndicates significant difference between landings.

^bIndicates significant difference between sides.

Table 2

Displays the mean time from initial contact to peak vGRF (s) recorded for the right and left leg during the first and second landings of a DVJ.

	1st landing	2nd landing	Average
Left	0.061	0.067	0.064
Right	0.057 ^a	0.067 ^a	0.061
Average	0.059 ^a	0.067 ^a	0.062

^bIndicates significant difference between sides.

^aIndicates significant difference between landings.