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Vertical Ground Reaction Force-Time Curve Differences Between the Two Landings of a Drop Vertical Jump. Implication For ACL Injury Risk

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ABSTRACT

Vertical drop jump consists two landings of which the first one is the most frequently analysed one. Aim of this paper was to compare kinetic patterns between first and second landings and dominant and non-dominant leg between landings by analysing force-time curves and their variability across landings. 44 top level female handball players (N = 25) and volleyball players (N = 19) of average age 24 ± 4 y, height 181.1 ± 7.8 cm and weight 72.4 ± 8.0 kg agreed to participate in this study. Each subject completed 4 successful drop jumps from an initial height of 30 cm on two parallel ground reaction force platforms. Force-time curve analysis revealed significant differences ($p < .05$) in certain parts of the cycle between the two landings for each leg. Moreover, significant differences ($p < .05$) were found between dominant and non-dominant leg solely in the second landing. Second landings were shown to be significantly more variable ($p < .001$) than the first ones. Results of the current study confirm previous findings of different neuromuscular pathways used in two landings thus indicating a possible increased risk of ACL injury which highlights the importance of second landing analysis in drop vertical jump.

Keywords: drop vertical jump; second landing; ground reaction force; neuromuscular control

INTRODUCTION

One of the functional tests most commonly used for knee injury risk assessment is drop vertical jump (DVJ) (Legnani et al., 2023). It is composed of two landings of which the first one includes a subsequent jump. First landings have more frequently been used to investigate DVJ and biomechanical parameters involved as well as its association with increased injury risk regardless of its controlled settings. Such instructed and well-controlled task has been shown to reduce the vertical ground reaction forces (vGRF) (McNair, Prapavessis, Callender, 2000; Prapavessis, McNair, 1999). A large vGRF exerted on a force platform over a short period of time creates a high rate of force development, which may provoke joint instability and increase the risk of anterior cruciate ligament (ACL) injury (Hewett et al., 2005). vGRF is also known to be dependent on the knee flexion angle (Podraza, White, 2010; Waxman et al., 2017) as well as to correlate with the change in muscle stiffness (Waxman et al., 2017; Devita, Skelly, 1992). As such, it is a good indicator of absorptive capability of the body. Therefore, lack of instructions regarding the second landing and perturbations caused by previous drop jump are sufficient to change muscle activity and kinetics (Ambegaonkar, Shultz, Perrin, 2011) possibly leaving a demeaning effect on neuromuscular control which is key in injury prevention.

Changes in joint kinetics and kinematics have previously been shown in terms of greater side-to-side differences in the second landings (Bates et al., 2013a) as well as timing differences where total landing phase duration decreases in the second landing while the time to peak vGRF increases slightly (Bates et al., 2013b). After analysing ground reaction forces and center of mass (CoM) between the two landings, Bates et al. (2013c) concluded that greater side-to-side asymmetry in vGRF and a higher CoM during impact suggests that the second landing may even be more representative of the in-game mechanics associated with increased ACL injury risk.

In a more detailed approach, vGRF can be observed as a time dependent variable even without regard to the peak value. Impulse as a force integral and rate of force development (RFD) are commonly used to represent force-time relation (Lees, Lake, 2008). However, force impulse does not represent the ever-variable position of the force-time curve, whereas RFD more closely relates to the amount of loading in the observed time interval. After using RFD to analyse countermovement jump (CMJ) after adaptations to training, Cormie et al. (2009) confirmed that such force-time analysis provides a more detailed insight into performance. They also suggested that changes in force-time curve might not only be the reflection of physiological adaptations but also mechanical ones.

Therefore, the aim of this research was to show the existence of any differences between the two landings when analysing force-time relation of vGRF. Moreover, we investigated side-to-side differences across the two landings as well as force-time curve variability across jump trials. Our hypothesis was that participants would show different development of force over time between the two landings of a DVJ. Also, we hypothesized that greater side-to-side asymmetry would be seen in the second landing along with greater force-time curve's variability across jump trials.

MATERIALS AND METHODS

Participants

Participants included in this study were 44 elite female handball (n = 25) and volleyball (n = 19) players of national rank (mass = 72.4 ± 8.0 kg, height = 181.1 ± 7.8 cm, age = 24 ± 4). DVJ testing was a part of a larger biomechanical study for pre-season screening purposes. Also, participants were not divided based on sport as that was not the topic of interest for this study. However, the inclusion criteria were full participation without any limitations in elite level performance and no current pain or discomfort of the musculoskeletal system. Testing procedures were approved by the institution's ethic committee and conducted in accordance with the Declaration of Helsinki and informed written consent was obtained from each participant.

Measurement protocol

For the purposes of the current study, kinetic data was acquired from ground reaction force (GRF) platform (Kistler Type 9286A, Winterthur, Switzerland). Prior to measurement, test trials were provided until participants felt familiarized with the task. Each participant performed 4 successful jumps. The subjects were instructed to stand on top of a 30-cm box with their feet positioned in a comfortable position not wider than the waist width with arms held on their sides. After dropping down from the box on the two GRF platforms, participants were instructed to minimize the time of con-tact for the first landing and to perform an immediate transition to the maximum vertical jump. No instructions were provided for the second landing. During the first landing, the subjects were also instructed to simultaneously land on both force platforms with separate feet allowing the acquirement of force data for both legs separately. If these conditions were not met, the trial was excluded from the analysis. Leg dominance was defined as self-reported kicking leg when asked to kick a ball for maximum distance (Ford, Myer, Hewett 2003).

Data processing methods

For the force-time curve analysis, landing phase from the point of initial contact to the point of maximum vGRF was used as in that period highest RFD occurs with the greatest potential of causing an injury. Data was processed within the SMART system (BTS Bioengineering, Padua, Italy). Each landing phase was automatically chosen by the software to exclude human bias in the point of initial contact of the foot and platform and at the point of maximum vGRF. To compare force-time curves between landings, normalization was made for both force and time parameters. Force was normalized to the maximum vGRF value of the belonging jump and time was expressed within a 100% of landing cycle. Therefore, a proper comparison of the force-time curve between two landings in different time intervals was allowed.

Statistical Analysis

Experimental data were collected and processed using SMART System, organized in the Microsoft Excel (2016) database and statistically evaluated using data analysis software system SPSS (v20).

Counting variables were presented by frequencies or percentages. Normally distribut-ed continuous variables (distribution tested with Shapiro-Wilk's test) were presented as means ± standard deviation or by median and interquartile range (IQR) otherwise.

Comparisons of normally distributed variables were done using parametric or non-parametric tests, where appropriate. Comparisons of mean normalized force (%maxF) values between first and second landing, as well as comparisons between dominant and non-dominant leg were made using paired t-test, while comparisons of mean variances between two landings, as well as between dominant and non-dominant leg, were done using Wilcoxon matched pairs test. The level of statistical significance was set at 0.05 in all analyses

RESULTS

Forty-four elite female handball (N = 25) and volleyball (N = 19) players were included in this study (24 ± 4 years; 181.1 ± 7.8 cm; 72.4 ± 8.0 kg). In our sample, 86% of the subjects self-reported their right leg to be the dominant one. All further data is presented according to leg dominance.

Statistically significant differences ($p < .05$) in %maxF were noted between the two landings when analyzing both legs separately.

Dominant leg (Figure 1) showed significant differences from 16 to 33% and 41 to 100% of landing cycle while non-dominant leg (Figure 2) showed significant differences from 0–3%, 19–37% and 48 to 100% of landing cycle.

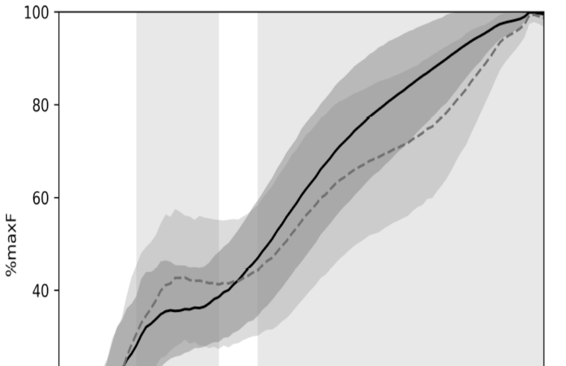

Figure 1. Analysis of mean value differences of %maxF between two landings within normalized time for the dominant leg. Shaded areas represent statistically significant differences ($p<.05$) from 16 to 33% and from 41 to 100% of cycle. Note. %maxF = force normalized as percentage of the maximum force value of the belonging jump

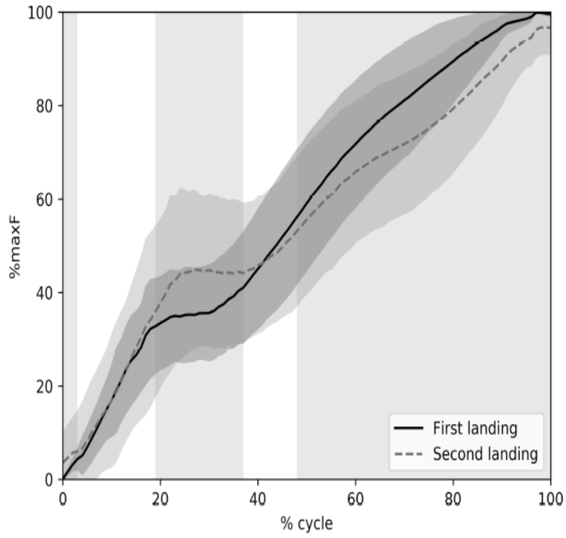

Figure 2. Analysis of mean value differences of %maxF between two landings within normalized time for the non-dominant leg. Shaded areas represent statistically significant differences (p<.05) from 0 to 3%, 19 to 37% and from 48 to 100% of cycle. Note. %maxF = force normalized as percentage of the maxi-mum force value of the belonging jump.

When analysing side-to-side differences in each landing (Figure 3 and 4), only the second one (Figure 4) revealed statistically significant differences (p < .05) in %maxF. Immediately following the initial contact, from 0 to 4% of landing cycle, non-dominant leg showed greater %maxF values. This also occurs from 27 to 42% of landing cycle. However, from 89 to 100% of landing cycle, dominant leg demonstrates significantly greater %maxF values.

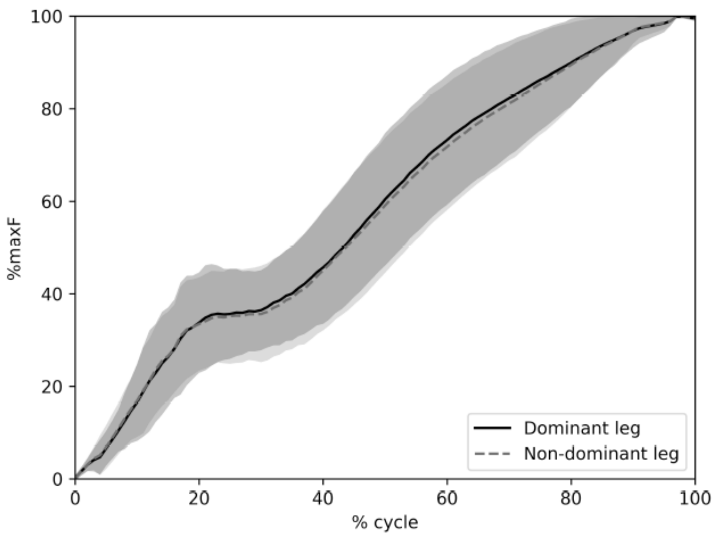

Figure 3. Analysis of mean value differences of %maxF between dominant and non-dominant leg in the first landings within normalized time. Note: %maxF = force normalized as percentage of the maximum force value of the belonging jump

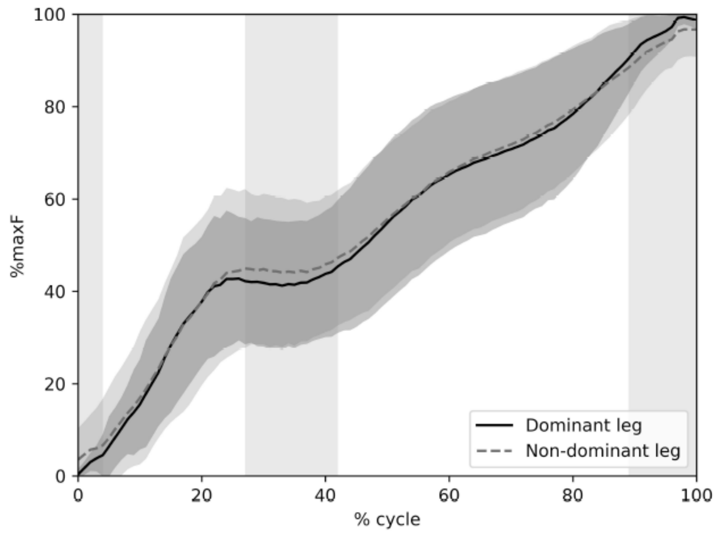

Figure 4. Analysis of mean value differences of %maxF between dominant and non-dominant leg in the second landings within normalized time. Shaded areas represent statistically significant differences (p<.05) from 0 to 4%, 27 to 42% and from 89 to 100%. Note: %maxF = force normalized as percentage of the maximum force value of the belonging jump.

Along with force-time curve values, their variability across repetitions was also quantified. To do so, variability was expressed as mean value of variance for each percent of cycle which allowed for between landings analysis. Significant differences (p < .001) were found between the two landings for both dominant and non-dominant leg (Table 1). After analyzing each landing separately, again only the second one showed significantly different variability between dominant and non-dominant leg (p < .001) which is presented in Table 1. When looking at individual areas of significantly different %maxF in the second landing between dominant and non-dominant leg, they all exhibit greater force-time curve variability for the non-dominant leg (Table 1).

Table 1. Comparison of %maxF variances between first and second landing and between dominant and non-dominant leg. Presented are means with SD.

	First landing	**Second landing**	**p**	**Second landing 0–4%**	**Second landing 27–42%**	**Second landing 89–100%**
Dominant leg	105.36 (66.88)	175.07 (93.64)	<.001	7.28 (8.13)	187.39 (9.00)	19.28 (18.18)
Non-dominant leg	107.1 (68.90)	204.25 (8.22)	<.001	66.70 (23.31)	243.38 (25.76)	53.97 (25.35)
p	.5	<.01		.04	<.001	<.001

Note: %maxF = force normalized as percentage of the maximum force value of the belonging jump.

DISCUSSION

The purpose of the current study was to compare kinetic parameters between the two landings of a DVJ. It was done by analysing the motion of the force-time curves within both landings as well as between dominant and non-dominant leg and the variability of the force-time curve between the landings for both legs. Thus far, majority of research has been based on insufficiently detailed data of the first landing. Results of this study point out to the importance of data interpretation which should include the force-time curve analysis and the importance of the second landing in biomechanical evaluation of injury risk. Differences shown here confirm previously explained biomechanical and neuromuscular singularity of the two landings.

To the author's knowledge, differences in vGRF force-time curves between the two landings of a DVJ haven't yet been shown. Cormie et al. (2009) concluded that observing the motion of the force-time curves is a more valuable method of analysis than the one using peak value variables which poorly explain the nature of neurophysiological adaptations. In their study, a group of jumpers managed to produce greater peak power in relation to non-jumpers by increasing the force-time curve gradient. Such increase coincides with greater rate of power development which is of great importance in the functional diagnostics of athletes. Results of our study point to differences in neuro-physiological patterns between the two landings. This is supported by significant periods of statistical difference in %maxF for both legs, which confirms the separate neuromuscular pattern across landings theory (Ambegaonkar, Shultz, Perrin, 2011; Bates et al., 2013a; Bates et al., 2013b; Bates et al., 2013c). In general, the second landing shows lower %maxF values, which supports the absorptive nature of the second landing. It was previously explained that the second landing is the one where most of the non-contact ACL injuries occur in basketball players (Ford, K. R., Myer, G. D., Hewett. 2003). Some of the reasons are per-turbations caused by the first landing and its subsequent jump which interfere with body control in the flight phase just before the second landing as well as with loss of focus after completing the key task the individual was instructed with. Bates et al. (2013c) assumed that the flight phase, which decreases the body control and the lack of verbal instructions for the second landing, lead to loss of focus and increase in joint stiffness. Further on, they showed kinematic differences where alterations in hip and knee flexion as well as in center of mass height indicate decreased neuromuscular control in the second landing and a physically more demanding task in general (Bates et al., 2013b; Bates et al., 2013c)), which explains lower contribution of H-reflex and consequently greater reliance on viscous muscle properties due to strictly absorptive tendomuscular work (Leukel et al., 2008). Therefore, like in most research, the instructions were given regarding the first landing where the subjects had to decrease the time of contact and jump vertically as high as possible.

Our results partially correlate with assumptions made above. Greater stiffness could relate to curve path from 16 to 33 % and 19 to 37 % for dominant and non-dominant leg, respectively. In those moments, the second landing's force-time curve continues its linear upslope unlike the first landing's curve. Although it happens in a short time window, it could be hypothesized that it is the reflection of greater lower extremity stiffness since it has been shown that increase in stiffness increases the vGRF (Waxman et al., 2017; Devita, Skelly, 1992; Myers et al., 2011). However, this does not explain the rest of the normalized time. By analysing the second landing's curve further (Figure 1 and 2), one can notice a sudden horizontal shift of greater amount than first landing's curve, which is what authors believe to be an adaptation to the absorptive nature of the second landing by regulation of the lower extremity stiffness. This horizontal shift, or even downfall in some subjects, gives an impression of two force peaks which has previously been noticed (Bates et al., 2013b). Unfortunately, the topic of interest to their study were kinematic variables at peak values exclusively. So even though they attribute kinematic differences in the second landing to increased joint stiffness, they haven't investigated kinematic behaviour throughout the time (Bates et.al., 2013a). In addition, Podraza and White (2010) reported the correlation between peak value of vGRF and knee flexion angle at the time of the landing. It could be assumed that the sudden loss of knee control can have an impact on the looks of vGRF curve as well as on the peak values. Nevertheless, this two-peaked curve phenomenon should be additionally investigated as authors believe that at the time of the first peak lies the great potential of breaking the kinetic chain of events due to high force impulse and high RFD.

Apart from the differences across the landings, significant differences were also shown regarding the laterality or side-to-side difference in loading between dominant and non-dominant leg in the second landing (Figure 4). This is similar observation to one that Bates et al. (2013a) noted when they analysed kinetic and kinematic differences between landings and found that there is greater side-to-side asymmetry in the second landing regarding hip sagittal and transverse plane rotation angles, hip sagittal plane and adduction moments, knee flexion angle and knee sagittal plane and adduction moments. Possibly the most interesting side-to-side asymmetry in our data happens in the beginning of the second landing, within the normalized time, where the non-dominant leg shows significantly higher values ($p < .01$) but after only 4% of the cycle, equalization with the dominant leg occurs. These results are not completely clear, but it could be assumed that non-dominant leg takes the role of the initial absorber after which the dominant one joins to control the loading. It is known that female soccer players have far less chance of injuring the dominant leg (Brophy et. al., 2010). Therefore, this could be a protective mechanism from the high initial force impulse on the dominant leg which is one of the causes of non-contact ACL injury. However, no such neuromuscular adaptation ability of the dominant and non-dominant leg has been reported so far.

Along with the curve motions, differences between the landings have been shown in relative vGRF variability across jump trials as well. Force-time curve in the second landing was significantly more variable across jump trials for both dominant and non-dominant leg ($p < 0.01$), which confirms increased body perturbations caused by the decrease in body control during the flight phase. Unlike the first landing, the second one also shows variability differences between legs throughout the entire landing phase ($p < .01$). Further on, when analysed separately, both areas of significant difference in %maxF between the dominant and non-dominant leg in the second landing showed greater variability values for the non-dominant leg ($p < 0.01$). Increased variability is a sign of poor landing repeatability which can be interpreted as decreased neuromuscular control.

Up to date, to the authors' knowledge, this is the first study that compared the force-time curve motions and the variability of the force-time curves between the landings of a DVJ. Our results confirm the previous conclusions that the second landing is characterized by decreased neuromuscular control (Bates et al., 2013a; Bates et al., 2013b; Bates et al., 2013c). Poor neuromuscular control has been singled out as the leading risk factor for ACL injury, and therefore, its detection is crucial in functional diagnostics and injury prevention.

Even though vGRF differences were found between the two landings, there are certain limitations to this study. The main one is a relatively small number of subjects compared to other similar studies. Greater number of subjects would most likely allow segregation of previously injured athletes, and in a prospective case, afterwards injured athletes. Also, the level of understanding the reported results would be higher if electromyographic and kinematic parameters were involved.

CONCLUSION

Results of the current study confirm the previous findings on different neuromuscular pathways used in two landings, thus indicating a possible increased risk of injury for several reasons. Firstly, in a major part of normalized time, force-time curves showed significant difference between landings for each leg, which suggests the use of different biomechanical and neurophysiological mechanisms. Secondly, greater side-to-side asymmetry in force-time curves between dominant and non-dominant leg was found within the second landing, which indicates distinct functional tasks. Lastly, increase in variability was observed for force-time curves in the second landing, which strongly points to the decrease in neuromuscular control. Findings of this study have meaningful implications in prevention of knee injuries through functional biomechanical analysis of both landings of a drop vertical jump task.

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