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Original Article

Correlations between sagittal plane kinematics and landing impact force during single-leg lateral jump-landings

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Abstract. [Purpose] The correlations of peak vertical ground reaction force and sagittal angles during single-leg lateral jump-landing with noncontact anterior cruciate ligament injury remain unknown. This study aimed to clarify the correlations between kinematics and impact force during lateral jump-landing. [Subjects and Methods] Twenty active males were included in the analysis. A sagittal-view movie camera and force plate were time synchronized. Trunk and lower extremity sagittal angles were measured 100 ms before initial contact and at peak vertical ground reaction force. Peak vertical ground reaction force, time between initial contact and peak vertical ground reaction force, and loading rate were calculated. [Results] The mean sagittal angle was 40.7° ± 7.7° for knee flexion during the flight phase and 16.4° ± 6.3° for pelvic anterior inclination during the landing phase. The mean peak vertical ground reaction force was four times the body weight. The median time to peak vertical ground reaction force was 63.8 ms. The knee flexion during the flight phase and pelvic anterior inclination angles during the landing phase were related to the peak vertical ground reaction force. [Conclusion] Increasing knee flexion and decreasing pelvic anterior inclination might reduce the impact during single-leg lateral jump-landing.

Key words: One-leg lateral landing, Flight phase kinematics, Ground reaction force

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INTRODUCTION

Noncontact anterior cruciate ligament (ACL) injuries often occur during single-leg jump-landing while playing basketball, handball, and other jump-landing sports1). The magnitude and patterns of vertical ground reaction force (VGRF) that represents the impact force during anterior jump-landing affect the valgus moment and tibial anterior shear force of the knee, potentially increasing mechanical stress on the ACL2, 3). In males, during single-leg anterior jump-landing, ACL strain was shown to peak at maximum ground reaction force (GRF)4). The peak VGRF (pVGRF) in males was reported to be larger than that in females5). Therefore, pVGRF during single-leg anterior jump-landing is a risk factor of noncontact ACL injury in males.

The VGRF magnitude during anterior jump-landing is greatest when knee flexion is 0–256). Attenuation of impact forces by increasing knee and hip flexion during anterior jump-landing reduces both pVGRF and ACL strain7–9), which suggests that the knee- and hip-flexion angles during anterior jump-landing may influence the risk of ACL injury by modifying the ACL loading magnitude affected by VGRF. As stated earlier, much is known about the biomechanics of anterior jumping.

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However, ACL injuries often occur during single-leg lateral jump-landing, not just during anterior jump-landing[1)]. The peak knee valgus and sagittal angles of the lower extremity during lateral jump-landing are different from those during anterior jump-landing for male athletes[10, 11)].

Noncontact ACL injuries tend to occur within 40 ms of foot contact with the ground[1)], faster than the reported voluntary knee and trunk activation times[12, 13)]. This suggests that GRF modification is difficult, even if control of the lower extremities and trunk position starts immediately after foot contact. During anterior jump-landing, preadjustment of the sagittal angles during pre-landing flight may be essential for controlling post-landing GRF patterns[14, 15)]. However, the correlations between sagittal kinematics and GRF patterns during lateral jump-landing remain unknown.

The purpose of this study was to determine the correlations between sagittal plane kinematics and GRF during single-leg lateral jump-landings in males. The hypothesis was that sagittal angles, including trunk, hip, and knee angles, during the flight and landing phases predict GRF patterns. Improved understanding of kinematic factors that influence GRF might facilitate more effective instruction or feedback for alignment control to attenuate the impact that strains the ACL during lateral jump-landing.

SUBJECTS AND METHODS

The inclusion criteria were males who were physically active, aged ≥18 years, and had no history of serious injury or surgery in the lower extremities or lumbar region. A power analysis for a regression model based on the kinematic and GRF data from the study of Yin et al.[16)] indicated that 20 participants would be necessary to attain an a priori power of 0.80. Therefore, 20 healthy male collegiate athletes were recruited. The subjects' characteristics (mean ± SD) were as follows: age, 21.0 ± 1.7 years; height, 172.2 ± 6.7 cm; and weight, 65.8 ± 8.0 kg. All the participants reported a mean duration of 8 h of weekly training or sports participation in basketball, handball, volleyball, and soccer during the 3 months immediately preceding the study. The institutional review board of Tokyo Medical and Dental University approved the study design (approval No. 1885). All the participants provided written informed consent to participate in the study.

Subject motions were recorded in the sagittal view by using a digital video camera (HDR-PJ590, Sony Corporation, Tokyo, Japan) at a sampling rate of 60 Hz to allow two-dimensional kinematic analysis of sagittal angles. VGRF data were collected with a force plate (260AA6, Kistler Instrumente AG, Winterthur, Switzerland) at a sampling rate of 1,000 Hz. The camera was mounted on a tripod and positioned in the jump direction based on the perspective of each participant (on a line extending from the midline of the force plate). The camera was positioned 335 cm from the lens to the center of the force plate at a height of 1 m from the center of the lens to the floor. A 25-cm high step was placed 60 cm from the center of the force plate. The height of the force plate surface was 5 cm above the ground level. Videographic and force plate data were time synchronized by using a synchronizer (PTS-110/2 LED, DKH Co., Ltd., Tokyo, Japan). Sagittal images and GRF data were acquired by using specific software (IFS-4 J/3 J, DKH).

The sagittal angles of the trunk and lower extremities during the flight phase, defined as 100 ms before initial contact (IC), and at pVGRF were measured by extracting corresponding video frames. The flight phase started after the participant jumped off the step and when the vertex of the head reached the highest point. The sagittal angles of the trunk and lower extremities that were indicated by markers in each frame were measured by using the Image J software (National Institutes of Health, Bethesda, MD, USA).

All the participants were clothed in identical athletic attire comprising spandex shirts, shorts, and shoes with no air cushions. Reflective markers were placed on the skin and shorts after the participants performed double-leg deep squats while wearing the shorts to ensure a customized fit in order to avoid proximal translation of the thigh during measurement. The markers (diameter, 14 mm) were affixed with doubled-sided adhesive tape to anatomical landmarks representing the trunk, thigh, and lower leg segments. Markers for the iliac spine and greater trochanter (GT) were affixed to the shorts. Marker placement was evaluated while the participants stood upright with their feet shoulder-width apart and hands inserted in the opposite axillae.

The trunk anterior lean angle was defined as the angle formed between a line joining the acromioclavicular joint and GT and a line perpendicular to the floor. The pelvic anterior inclination angle was defined as the angle formed between a line joining the anterior and posterior superior iliac spine. The hip flexion angle was defined as the relative change in angle between the pelvic anterior inclination and thigh angles as compared with that while standing naturally. The knee flexion angle was defined as the relative angle between the thigh and the shank. The thigh was defined as the line joining the GT and the lateral joint space (LJS) at the midpoint of the knee. The shank was defined as the line joining the LJS and the lateral malleolus.

The participants performed a 5-min warm-up of stationary bicycling without resistance and light stretches. They were then verbally and visually instructed on how to perform the jump-landing tasks. Then, reflective markers were placed and evaluated, and task performance was assessed. Kinematic data were collected from the dominant leg of each participant, defined as the leg used to kick a ball to maximal distance[7, 14)]. Seventeen of the 20 participants were right-leg dominant.

All the participants practiced five single-leg lateral jump-landing tasks to become accustomed to the movements before data collection. They stood on the step on their dominant leg with the knee of the other leg bent at approximately 90°, with neutral hip rotation, arms crossed, and hands inserted in the opposite axillae to eliminate the effect of arm movement. The participants then jumped sideways without intentional upward action and landed as naturally as possible on the same leg on the center of the force plate and maintained balance for 5 s. They faced forward during all jumps and landings. The task was repeated three times in succession. A trial was deemed unacceptable if part of the sole of the foot fell outside the force plate at landing, the foot moved or slid after landing, and/or if the sole of the opposite foot touched the force plate or floor. Trials considered failures were determined visually, and feedback on landing performance was withheld.

The factors analyzed from the VGRF data included pVGRF, time to pVGRF, and loading rate. pVGRF was normalized by body mass (%). IC was defined as the moment when VGRF exceeded 10 N. The time to pVGRF was defined as the interval between IC and the instance of pVGRF7). Theoretically, the interval between foot contact and pVGRF is important for reflexes and as a central control strategy for absorbing the impact of landing17). The loading rate was calculated as pVGRF divided by the elapsed time from IC to pVGRF18). The same individual measured the sagittal angles and analyzed the GRF data. Intraclass correlation coefficients (ICCs 1, 3) were calculated to estimate intrarater reliability.

The values of all the variables were averaged over three jump-landing tasks and analyzed19, 20). The normal distribution of each variable was determined with the Shapiro-Wilk normality test. Correlations between the VGRF variables and the sagittal angles during the flight and landing phases were initially assessed by using a series of simple correlational analyses. Variables with significant simple correlations ($p<0.05$) were then entered into separate forward stepwise multiple linear regression analyses to determine the collective influence of the sagittal angle on VGRF, time to pVGRF, and loading rate. Variance inflation factors for each regression model were assessed to determine multicollinearity. A variance inflation factor of >10.0 was considered to indicate multicollinearity within a regression model14). Correlations between the sagittal angle at the flight and landing phases were assessed with simple correlational analyses. The a priori α level was 0.05. Data were analyzed with SPSS v. 21.0 (IBM Corp., Armonk, NY, USA).

RESULTS

All the participants performed all the tests, and all datasets were complete. Trial outcomes were unacceptable in 10 participants. The average number of unacceptable trials was 1.0 (range, 0–4) for the 20 participants. Table 1 shows the intrarater reliability for the measured variables. All the coefficients had high ICCs (range, 0.73–0.97; Table 1). Except for time to pVGRF and loading rate, distribution normality was confirmed for all the variables.

Table 2 shows the sagittal angles and GRF variables during the flight and landing phases. The mean sagittal angle was 40.7° ± 7.7° (95% confidence interval [CI], 37.1–44.4) for knee flexion and 15.0° ± 6.1° (95% CI, 12.1–17.8) for the pelvic anterior inclination during the flight phase. The mean pVGRF was about fourfold greater than body weight (404 ± 92; 95% CI, 361.2–447.4), and the median time to pVGRF was 63.8 ms.

Table 3 shows the correlations between the sagittal angles during the flight and landing phases and the VGRF parameters. Knee flexion and pelvic anterior inclination angles were significantly associated with pVGRF and time to pVGRF at both phases. Knee flexion at both phases and pelvic anterior inclination at the landing phase were significantly associated with loading rate.

The variance inflation factor never exceeded 2.0 in all the regression models, indicating that multicollinearity did not influence the results. The knee flexion angle at the flight phase and pelvic anterior inclination angle at the landing phase predicted approximately 50% of the variance in pVGRF ($R^2=0.499$, $p=0.003$; Table 4). The pelvic anterior inclination angle at the landing phase predicted approximately 37% of the variance in time to pVGRF ($R^2=0.368$, $p=0.005$; Table 4). The knee flexion and pelvic anterior inclination angles during the flight and landing phases were positively correlated ($R=0.635$, $p=0.003$ and $R=0.955$, $p<0.001$, respectively).

DISCUSSION

The key findings were that the knee flexion during the flight phase and pelvic anterior inclination angles during the landing phase significantly predicted pVGRF during single-leg lateral jump-landings in the male athletes. These findings suggest that decreased knee flexion 100 ms before landing and increased pelvic anterior inclination during the landing phase increase vertical impact force.

Several studies have shown a causal relationship between the sagittal angles of the lower extremities and GRF in forward and upward jump-landing tasks. Attenuation of impact forces by increasing knee and hip flexion during double-leg anterior jump-landing reduces pVGRF7–9). From these findings, a larger trunk anterior lean, hip flexion, and knee flexion during the flight and landing phases can be speculated to reduce the impact in the single-leg lateral jump-landing task described herein. The knee prediction was supported, whereas the trunk and hip predictions were not. One reason for this might be the effect of direction on jump-landing. Sinsurin et al.11) analyzed the effects of jump direction on sagittal angles of the lower extremities and found less hip flexion during the landing phase after single-leg lateral jumps than after anterior jumps. The lower-extremity sagittal angles and GRF could also differ during landing in single- and double-leg jumps21). The above-mentioned findings suggest that the kinematics of landing from anterior jumps cannot be applied to those of lateral jumps and that kinematic data should be task specific for single-leg lateral jump-landings, as applied in the present study.

Knee flexion during the flight phase correlated negatively with impact force during single-leg lateral jump-landings. In the present study, the knee flexion angle 100 ms before landing was 40.7° ± 7.7° and pVGRF was 404 ± 92% of the body weight

Table 1. Intrarater reliability for measured variables

Variable	ICC (95% CI)
Flight phase angles	
Trunk anterior lean	0.97 (0.94–0.99)
Pelvic anterior inclination	0.97 (0.93–0.99)
Hip flexion	0.93 (0.86–0.97)
Knee flexion	0.73 (0.44–0.89)
Landing phase angles	
Trunk anterior lean	0.97 (0.95–0.99)
Pelvic anterior inclination	0.94 (0.88–0.98)
Hip flexion	0.90 (0.78–0.96)
Knee flexion	0.85 (0.68–0.93)
pVGRF (% body weight)	0.91 (0.81–0.96)
Time to pVGRF (ms)	0.97 (0.94–0.99)

ICC: intraclass correlation coefficients (1, 3); CI: confidence interval; pVGRF: peak vertical ground reaction force; Time to pVGRF: time between initial contact and pVGRF

Table 3. Correlations between sagittal angles at flight and landing phases, and vertical ground reaction force parameters

	pVGRF	Time to pVGRF	Loading rate
	r	r	r
Flight phase angles			
Trunk anterior lean	0.041	−0.106	−0.221
Pelvic anterior inclination	0.439*	−0.545*	0.312
Hip flexion	−0.222	0.155	−0.362
Knee flexion	−0.564*	0.486*	−0.513*
Landing phase angles			
Trunk anterior lean	0.145	−0.224	−0.134
Pelvic anterior inclination	0.562*	−0.606*	0.396*
Hip flexion	0.075	−0.094	−0.135
Knee flexion	−0.549*	0.502*	−0.521*

pVGRF: peak vertical ground reaction force; time to pVGRF: time between initial contact and pVGRF; loading rate: pVGRF/time to pVGRF; F: flight phase; L: landing phase.
*Significant correlation at $p<0.05$

Table 2. Sagittal angles during flight and landing phases, and ground reaction force variables during single-leg lateral jump-landing tasks (n=20)

Body segments and joints	Flight phase (°)	Landing phase (°)
Trunk anterior lean	17.5 ± 4.7 (15.3, 19.7)	17.9 ± 4.9 (15.6, 20.3)
Pelvic anterior inclination	15.0 ± 6.1 (12.1, 17.8)	16.4 ± 6.3 (13.4, 19.4)
Hip flexion	25.8 ± 7.7 (22.2, 29.4)	27.1 ± 7.3 (23.7, 30.5)
Knee flexion	40.7 ± 7.7 (37.1, 44.4)	40.7 ± 6.0 (38.0, 43.6)
VGRF parameters		
pVGRF (% body weight)	404.3 ± 92.2 (361.2, 447.4)	
Time to pVGRF (ms)	Median 63.8; Range 64.7	
Loading rate	Median 6.2; Range 49.4	

Data are shown as mean ± standard deviation (95% confidence interval). Flight phase, 100 ms before initial contact; landing phase, instant of peak ground reaction force; VGRF: vertical ground reaction force; pVGRF: peak vertical ground reaction force; time to pVGRF: time between initial contact and pVGRF; loading rate: pVGRF/(time to pVGRF)

Table 4. Regression model coefficients

		Unstandardized coefficients		Standardized coefficients		
Dependent variable	Predictor variable	β	SE	β	R^2	n
pVGRF	F. Knee flexion	−5.312	2.127	−0.445	0.499	20
	L. Pelvic anterior inclination	6.424	2.587	0.442		
Time to pVGRF	L. Pelvic anterior inclination	−1.636	0.506	−0.606	0.368	20
Loading rate	L. Knee flexion	−0.921	0.356	−0.521	0.271	20

pVGRF: peak vertical ground reaction force; time to pVGRF: time between initial contact and pVGRF; loading rate: pVGRF/time to pVGRF; F: flight phase; L: landing phase

of each participant. The knee joint is the major shock absorber during foot contact with the ground[22, 23]. During single-leg lateral jump-landing, neuromuscular preparation to increase knee flexion before landing might reduce the impact force during the landing phase.

A positive correlation was found between landing-phase pelvic anterior inclination and landing impact force during single-leg lateral jump-landings. In the present study, the pelvic anterior inclination angle at the instance of pVGRF was 16.4° ± 6.3°. Most gymnasts flex the lumbar spine immediately before initial contact until the instance of pVGRF during drop-landing tasks[24)]. Such lumbar flexion might be preparation or reaction with the aim of absorbing kinetic energy caused by impact force, which might be more difficult for athletes to absorb if pelvic anterior inclination increases excessively during the landing phases. Jamison et al. found a positive correlation between surface electromyographic amplitude of the trunk erector muscle (L5 level) and knee valgus moment at landing during unanticipated side-step cutting tasks[25)]. They suggested that increased erector muscle activity increases spine stiffness, resulting in greater demand on the lower extremities to absorb upper-body kinetic energy during the landing phase.

Pelvic anterior inclination during the landing phase might change with the balance between the activity of the lumbar erector and those of the abdominal muscles responsible for pelvic anterior inclination[26)]. Although muscle activity was not measured, lumbar erector muscle activity could have increased during the landing phase, causing the pelvis to incline forward, thus inhibiting shock absorption. However, an excessive increase in pelvic posterior inclination and lumbar spine flexion might increase lumbar disk and ligament mechanical stress[24)]. Controlling pelvic posterior inclination while inhibiting excessive anterior inclination is important for preventing low back pain. Araujo et al.[27)] reported that core-stability training to control the neutral alignment of the pelvis and lumbar spine can reduce impact force upon landing. Thus, controlling the activity of muscles that stabilize the lumbopelvic region and position during flight might reduce impact during landing.

The present findings suggest that preparation to bend the knee appropriately and suppress pelvic anterior inclination is important for cushioning against impact force during single-leg lateral jump-landings. This information might be useful for evaluating in the sagittal position the flight to landing phases and for providing instruction on how to control the impact force that contributes to ACL strain. That is, if markers are affixed to bony points and single-leg lateral jump-landing tasks are recorded in the sagittal plane by using a standard digital video camera with the setup described herein, physiotherapists or trainers could compare pelvic anterior inclination and knee flexion angles with the reference values. Furthermore, this would help them to provide more specific information or feedback to athletes on controlling pelvic and knee sagittal angles in order to facilitate landings with the least impact possible. However, definitive clinical actions cannot be recommended until interventional studies determine the effects of instruction or feedback about the relevance of sagittal alignment on controlling impact force and the effects of knee loading, such as tibial anterior shear force, calculated using kinematic models.

Active young males participating in jump-landing sports were recruited in the present study. Because lower-extremity kinematics during the flight and landing phases vary according to gender, activity level, and sport[5, 15, 28)], these findings may not apply to all athletes. However, ankle joint angles or correlations between the ankle plantar flexion angle and pVGRF at landing were not analyzed, which should also be considered in males[5)]. Two-dimensional images to measure sagittal angles were used, which might have resulted in larger or smaller angles due to femur or tibia rotation, among other issues. An increase in knee joint valgus deviation was displayed in two-dimensional sagittal assessments as an increase in knee flexion followed by a smaller impact and decreased risk of ACL injury, although risk might increase due to the mechanism of inward rotation associated with valgus deviation. To account for this, the participants faced forward during lateral jump-landing to reduce variation in body movement along the horizontal plane. Moreover, angle data reproducibility was confirmed before further analyses.

The most important findings of the present study were that the knee flexion and pelvic anterior inclination angles during the flight phase were associated with pVGRF during single-leg lateral jump-landings in males, for whom increasing knee flexion and suppressing pelvic anterior inclination during the flight phase might reduce impact force.

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