

Article

Biomechanical Symmetry during Drop Jump Landing and Takeoff in Adolescent Athletes Following Recent Anterior Cruciate Ligament Reconstruction

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Abstract: This study investigated asymmetry between lower extremities during the landing and takeoff phases of a vertical drop jump (VDJ) in adolescent athletes following anterior cruciate ligament reconstruction (ACLR) and examined if performance was affected by reducing jump height. Thirty-three athletes who underwent ACLR and were referred for 3D biomechanical assessment before returning to play (mean age 15.9, SD 1.3 years; 16/33 female; mean time since surgery 7.4, SD 1.2 months) completed the VDJ while kinematics and kinetics were collected using motion capture. Lower extremity symmetry was compared between phases using paired t-tests. Jump height was calculated to measure performance. Asymmetries in ankle inversion, ankle adduction, knee adduction, hip adduction, hip adduction moment, and hip rotation moment were observed in both phases. Asymmetry was also observed in both phases for sagittal moments and power integrals at the knee and ankle and total power integral, with the magnitude of asymmetry being smaller during takeoff for power absorption/generation. Jump height was related to power generation integrals during takeoff but not to the asymmetry of power generation. Since asymmetries are translated from landing through takeoff, rehabilitation should address both phases to decrease injury risk and maximize performance after return to play.

Keywords: motion analysis; vertical drop jump; return to sport; ACL injury

1. Introduction

Anterior cruciate ligament (ACL) injuries have become increasingly common in adolescent athletes in the past two decades with the number of ACL tears increasing by 2.3% per year in youth 6 to 18 years of age [1,2]. This increase has been influenced by a greater number of adolescents participating in organized, high-level sports [1]. Studies have found a number of biomechanical factors, such as dynamic knee valgus and greater side to side knee abduction moment asymmetry, that contribute to a higher risk of sustaining an ACL injury [1,3–5]. Surgical reconstruction of the ACL is the preferred treatment to allow for patients to return to their prior level of activity [6,7]. McCollough et al. found that 63% of high school athletes did return to their sport following ACL reconstruction (ACLR). However, just 43% of athletes who returned to sport felt that they were playing at their pre-injury level of performance [8]. Research has shown that athletes returning to sport after ACLR have an increased risk of sustaining a new injury to both the ipsilateral and contralateral limbs and developing early onset osteoarthritis (OA) in the reconstructed knee even with successful surgery [9,10].

Due to this increased risk of sustaining a second ACL injury, there is much debate over the objective clinical criteria used to determine when an adolescent athlete should be

allowed to return to sport following ACLR [5,10–13]. Some of the commonly used return to sport measures include time since surgery, movement analysis, and the strength and range of motion symmetry between limbs [5,14]. In addition, physical performance tests that include hopping and jumping are also often used clinically to examine knee stability and return to sport readiness [5,14,15].

The vertical drop jump (VDJ) test is one such measure commonly used as it mimics a deceleration task often seen in sport and is a way to assess limb symmetry during a single movement [11,16,17]. In addition, it has been shown that uninjured adolescents perform a VDJ task with only slight asymmetries, supporting that biomechanical symmetry is an appropriate goal for return to sport testing [18]. The landing phase of this task has been extensively researched as this is the point when most non-contact ACL injuries are thought to occur [19–21]. Research has shown that poor biomechanics are present in patients following ACLR in tasks such as the VDJ landing [11,19,22]. Mueske et al. found that there is decreased energy absorption, decreased sagittal plane external flexion moments at the knee and ankle, and decreased peak dorsiflexion angle during the landing phase in adolescent athletes who had undergone ACLR compared to their uninvolved side [23]. Dynamic valgus, reduced active shock absorption, and decreased flexion of the lower extremity seen during the landing phase of the VDJ task have been associated with an increased risk for ACL injury [20,24–26].

The takeoff phase of the VDJ task has been less researched as it is normally used as a performance-based measure [27,28]. Little is known about the takeoff phase and how it relates to between limb symmetry following ACLR. Currently, no study has examined the biomechanical strategies utilized during both the landing and takeoff phases in the VDJ task and their implications in rehabilitation following ACLR. The purpose of this study was to investigate the occurrence and degree of asymmetries of kinetics and kinematics between the lower extremities during the landing and takeoff phases of a VDJ task in adolescent athletes following recent ACLR. We hypothesized that asymmetries seen in the landing phase will carry over to the takeoff phase, which will likely lead to decreased performance from a reduced jump height.

2. Materials and Methods

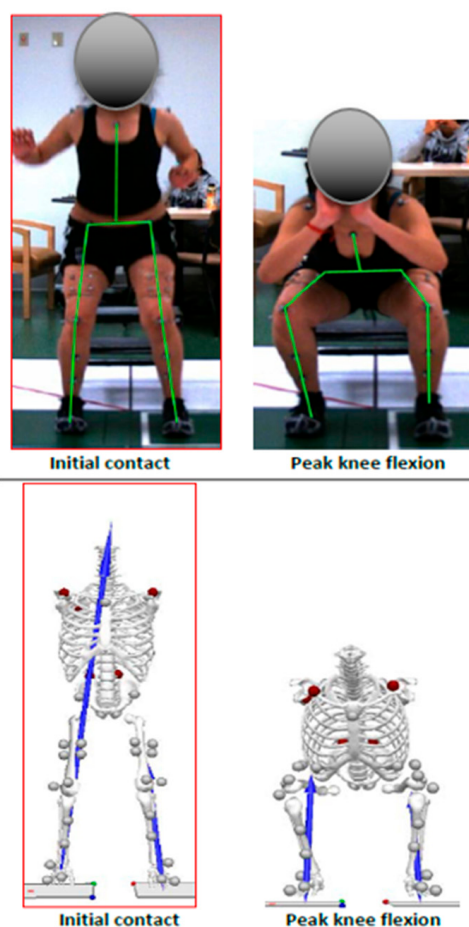
This retrospective study examined data from patients 13 to 18 years old who were seen in the Motion and Sports Analysis Laboratory between March 2015 and February 2018 for 3D biomechanical assessment following unilateral ACLR for a non-contact injury (Table 1). Patients were excluded from the study if they had a history of other serious lower extremity injury, previous ACL injury, were unable to complete the VDJ, or had missing motion analysis data during VDJ landing and takeoff. Patients had not yet been cleared for return to full activity at the time of testing. Data were accessed retrospectively under either a waiver of consent or signed consent approved by the Children's Hospital Los Angeles Institutional Review Board.

Data collection was performed by two experienced pediatric physical therapists who had specialized training in sports biomechanical assessment and motion analysis. Anthropometric measurements were obtained using standard clinical procedures, and a VDJ was performed as part of a more extensive biomechanical testing protocol [29]. Prior to all biomechanical testing, the subject warmed up with approximately 5 min of treadmill running. For the VDJ task, participants were instructed to drop off a 41 cm box, land with each foot on a different force plate, and then jump straight up as high as possible, landing back on the same force plates to keep the jump vertical (Figure 1). Following two to three practice trials, three trials for data collection were performed, and all trials with useable data (a minimum of two per subject) were averaged for further analysis [30].

Table 1. Participant characteristics (N = 33).

Characteristic	Value
Sex	
Female	16 (48%)
Male	17 (52%)
Age (years)	15.9 (1.3)
Height (cm)	170.2 (10.4)
Weight (kg)	69.6 (17.4)
BMI (kg/m ²)	24.0 (5.4)
Time since surgery (months)	7.4 (1.2)
Graft type (all autograph)	
Hamstring tendon	13 (39%)
Patella tendon	13 (39%)
Quadriceps tendon	6 (18%)
Iliotibial band	1 (3%)
Surgical side	
Left	22 (67%)
Right	11 (33%)
Meniscal involvement *	
None	18 (56%)
Repair	13 (24%)
Menisectomy	3 (9%)
Single sport	19 (59%)
Multiple Sports	14 (41%)

Continuous variables are reported as mean (SD). Categorical variables are reported as N (%). * 1 subject had both repair and menisectomy.

**Figure 1.** Vertical drop jump task performance.

Three-dimensional lower extremity motion analysis data were recorded during the VDJ using an 8 to 10 camera motion capture system at 120 Hz (Nexus 2, Vicon Motion Systems Ltd., Oxford, UK) and two analog force plates at 2400 Hz (AMTI OR6-5, Advanced Medical Terminology, Inc., Watertown, MA, USA). An experienced physical therapist placed markers on the participant's trunk, pelvis, and lower extremities following a custom 6-degree of freedom (DOF) model [30]. Marker trajectories were filtered using a Woltring filter with a mean squared error of 10 mm². Force plate data were filtered using a 16 Hz Butterworth filter.

Kinematic and kinetic measures were calculated during the landing and takeoff phases of the VDJ task. The landing phase was defined as the first initial contact to sacral marker velocity change of vertical direction, and the takeoff phase was defined as sacral marker velocity change of vertical direction to foot off. Kinematics were calculated based on segment orientations determined by 6DOF segment optimization in Visual3D (C-Motion, Inc., Germantown, MD, USA), and kinetics were calculated using inverse dynamics in the same software. Average joint angles, external moments and power in the sagittal, frontal and transverse planes were collected and used to calculate limb symmetry as the surgical limb minus the contralateral limb. Positive values indicate flexion, adduction, and internal rotation of the hip and knee and dorsiflexion, adduction, and inversion of the ankle, along with the corresponding external moments. The power integral was calculated during landing as the integral of power absorption (negative values) over the landing phase. Similarly, the power integral was calculated during takeoff as the integral of power generation (positive values) over the takeoff phase. In both cases, the integral is reported as a positive value indicating energy absorption during landing and energy generation during takeoff.

Jump height (H_{jump}) was calculated as a measure of performance using the impulse-momentum method based on the integral of vertical ground reaction force (GRF) from peak knee flexion (PKF) to foot off [31].

Equation (1):

$$H_{jump} = \frac{v_{takeoff}^2}{2g}, \quad (1)$$

where g is the acceleration due to gravity and $takeoff$ velocity is

Equation (2):

$$v_{takeoff} = \int_{PKF}^{footoff} \left(\frac{F_{GRF}}{m} - g \right) dt, \quad (2)$$

where F_{GRF} is the total (left + right) vertical GRF, and m is subject mass.

Difference between limbs (significance of asymmetry) during each phase and difference in magnitude of asymmetry between the landing and takeoff phases were evaluated using paired t-tests. The relationship of jump height to power generation integral at each joint and in total was evaluated using Pearson's correlation. Pearson's correlation was also used to examine the relationship between jump height and asymmetry of power generation. All statistical analysis was performed in Stata (version 14, StataCorp LLC, College Station, TX, USA) with a significance level of 0.05.

3. Results

Thirty-three patients (16 female; mean age 15.9, standard deviation (SD) 1.3 years) met the eligibility criteria and were included in this study (Table 1). Their mean time since surgery was 7.4 months (range 6 to 10 months). All patients had autograft reconstructions, 13 with hamstring tendon, 13 with patellar tendon, 6 with quadriceps tendon, and 1 with iliotibial band.

Kinematics and Kinetics:

In the frontal and transverse planes, significant asymmetry was observed, with the surgical limb having higher values during both landing and takeoff for ankle inversion, knee adduction, ankle adduction, and hip rotation (Table 2). The hip was less abducted on

the surgical side during both landing and takeoff, but the difference only reached statistical significance during landing. The hip adduction moment and ankle adduction moment were significantly lower on the surgical side during both landing and takeoff. Knee and hip rotation moment were lower on the surgical side during both landing and takeoff, but the difference only reached statistical significance during landing. The magnitude of asymmetry was greater during landing than during takeoff for hip abduction angle and moment, ankle adduction moment, and hip rotation moment.

In the sagittal plane, asymmetry was observed during both landing and takeoff for ankle, knee, and hip angles, ankle and knee flexion moments, ankle and knee power integrals, and total power integral. Angles, moments, and power integrals were lower for the surgical compared with the contralateral side. The magnitude of asymmetry was greater during landing than during takeoff for ankle and knee angles and moments and the power integral at all joints and in total. At the hip, flexion moments were higher for the surgical limb during both landing and takeoff, but the difference was only statistically significant during landing (Figure 2).

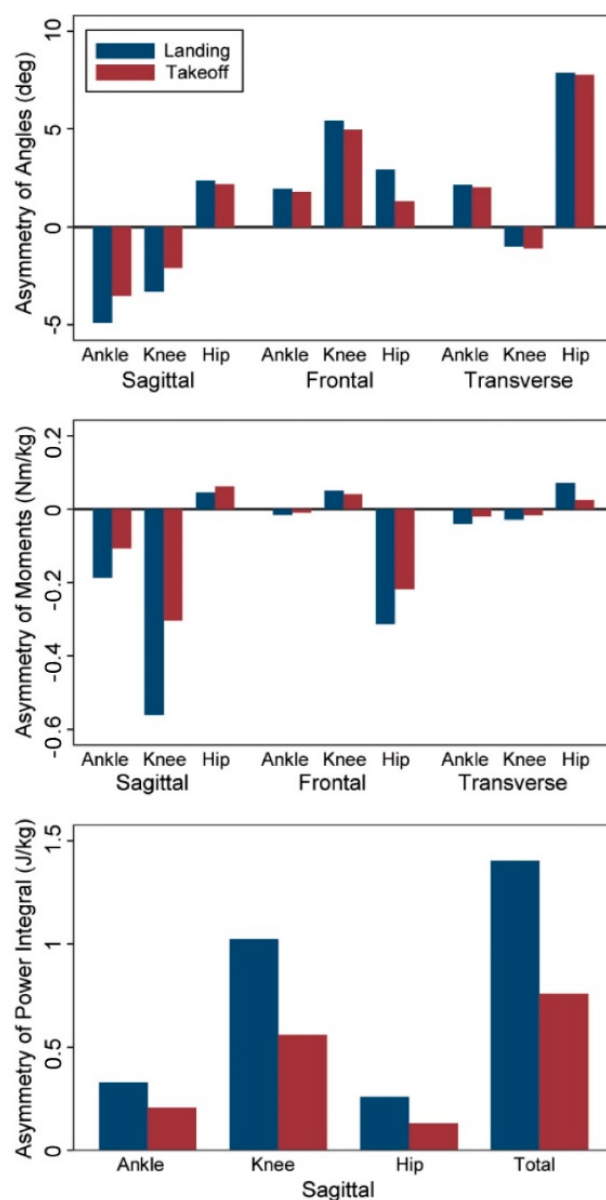


Figure 2. Asymmetry of kinematics and kinetics (difference between operated side and contralateral side).

Table 2. Kinematics and kinetics of the reconstructed and contralateral limbs during vertical drop jump (VDJ) landing and takeoff.

	Landing				Takeoff				
	Injured, Mean (SD)	Contralateral, Mean (SD)	Asymmetry, Mean (SE)	<i>p</i>	Injured, Mean (SD)	Contralateral, Mean (SD)	Asymmetry, Mean (SE)	<i>p</i>	P Asymmetry TO vs. Landing
FRONTAL PLANE									
Ankle inversion	9.3 (4.5)	7.3 (4.2)	2.0 (0.7)	0.01	10.9 (4.5)	9.0 (4.2)	1.8 (0.7)	0.01	0.61
Knee adduction	8.8 (7.1)	3.4 (6.5)	5.4 (1.1)	<0.0001	7.6 (7.0)	2.7 (6.2)	5.0 (1.1)	0.0001	0.22
Hip adduction	−8.2 (8.1)	−11.1 (6.8)	2.9 (1.3)	0.04	−7.8 (7.5)	−9.1 (6.5)	1.3 (1.1)	0.26	0.02
Ankle inversion moment	0.03 (0.06)	0.05 (0.08)	−0.02 (0.01)	0.20	0.09 (0.06)	0.10 (0.08)	−0.01 (0.01)	0.34	0.47
Knee adduction moment	−0.17 (0.18)	−0.22 (0.25)	0.05 (0.04)	0.18	−0.10 (0.13)	−0.14 (0.19)	0.04 (0.03)	0.16	0.69
Hip adduction moment	−0.11 (0.22)	0.20 (0.21)	−0.31 (0.05)	<0.0001	−0.02 (0.21)	0.20 (0.20)	−0.22 (0.04)	<0.0001	0.0001
TRANSVERSE PLANE									
Ankle adduction	3.4 (4.5)	1.3 (5.2)	2.2 (0.9)	0.02	2.9 (4.7)	0.9 (4.9)	2.0 (0.9)	0.02	0.63
Knee rotation	−10.6 (10.3)	−9.5 (9.0)	−1.0 (1.4)	0.47	−12.8 (9.3)	−11.7 (8.6)	−1.1 (1.2)	0.37	0.87
Hip rotation	12.1 (7.9)	4.2 (6.7)	7.9 (1.2)	<0.0001	11.3 (8.4)	3.5 (7.5)	7.8 (1.2)	<0.0001	0.86
Ankle adduction moment	0.11 (0.06)	0.15 (0.06)	−0.04 (0.01)	0.002	0.16 (0.06)	0.18 (0.07)	−0.02 (0.01)	0.03	0.02
Knee rotation moment	0.001 (0.04)	0.03 (0.07)	−0.03 (0.01)	0.05	0.01 (0.04)	0.03 (0.05)	−0.02 (0.01)	0.13	0.21
Hip rotation moment	0.03 (0.11)	−0.04 (0.11)	0.07 (0.02)	0.001	−0.02 (0.10)	−0.05 (0.10)	0.02 (0.02)	0.12	0.003
SAGITTAL PLANE									
Ankle dorsiflexion	17.2 (5.7)	22.1 (5.2)	−4.9 (0.8)	<0.0001	15.0 (5.5)	18.6 (5.9)	−3.5 (0.6)	<0.0001	0.006
Knee flexion	85.5 (13.0)	88.8 (11.9)	−3.3 (0.7)	0.0001	79.3 (12.2)	81.5 (11.7)	−2.1 (0.5)	0.0001	0.02
Hip flexion	84.9 (11.7)	82.6 (12.0)	2.4 (0.7)	0.001	77.5 (11.1)	75.3 (11.0)	2.2 (0.6)	0.0009	0.61
Ankle dorsiflexion moment	0.65 (0.17)	0.84 (0.27)	−0.19 (0.04)	0.0002	0.74 (0.19)	0.84 (0.23)	−0.11 (0.03)	0.0002	0.03
Knee flexion moment	0.84 (0.34)	1.40 (0.36)	−0.56 (0.09)	<0.0001	0.70 (0.27)	1.00 (0.24)	−0.30 (0.05)	<0.0001	<0.0001
Hip flexion moment	1.05 (0.19)	1.01 (0.34)	0.05 (0.06)	0.44	1.10 (0.23)	1.03 (0.24)	0.06 (0.03)	0.04	0.76
Power integral ankle	0.51 (0.14)	0.83 (0.32)	−0.32 (0.05)	<0.0001	0.78 (0.19)	0.97 (0.23)	−0.19 (0.03)	<0.0001	0.005
Power integral knee	1.10 (0.52)	2.07 (0.54)	−0.97 (0.13)	<0.0001	1.03 (0.46)	1.55 (0.38)	−0.52 (0.07)	<0.0001	<0.0001
Power integral hip	0.98 (0.24)	1.02 (0.40)	−0.05 (0.06)	0.46	1.17 (0.36)	1.17 (0.38)	0.002 (0.03)	0.94	0.01
Power integral total	2.59 (0.65)	3.92 (0.95)	−1.33 (0.21)	<0.0001	2.98 (0.80)	3.68 (0.80)	−0.70 (0.09)	<0.0001	0.0002

External moments are reported. Angles are in units of degrees, moments in Nm/kg, and power integral in J/kg.

Jump Height:

Jump height, as a measure of performance, was significantly related to the power generation integral during takeoff at all joints and in total regardless of limb injury status ($p \leq 0.05$) (Table 3). However, jump height was not related to asymmetry of the power integral at any joint or in total ($p \geq 0.52$).

Table 3. Correlation of jump height to power generation integral (AUC) during takeoff.

	Surgical		Contralateral		Asymmetry	
	R	<i>p</i>	R	<i>p</i>	R	<i>p</i>
Ankle power integral	0.40	0.02	0.41	0.02	−0.12	0.52
Knee power integral	0.34	0.05	0.50	0.003	−0.09	0.63
Hip power integral	0.50	0.003	0.45	0.009	0.05	0.77
Power integral total	0.51	0.002	0.57	0.0005	−0.02	0.90

4. Discussion

Reduced active shock absorption and decreased flexion of the lower extremity seen during the landing of jumping or cutting tasks are factors that have been associated with an increased risk for obtaining an ACL injury [24,26,32]. The current study found that asymmetries in shock absorption occurred during the landing phase of the VDJ for the ankle and knee, and that energy absorption during landing was lower overall on the surgical limb compared to the contralateral side. This decreased energy absorption could contribute to inadequate shock absorption at the knee joint which has been shown to be one risk factor associated with ACL injury during landing and cutting tasks [33,34].

Previous studies have shown that between limb asymmetries are often seen as the surgical limb offloading to the contralateral limb during the landing phase of the VDJ task, though specific asymmetric strategies differ by study [12,26,35,36]. Our study found decreased energy absorption on the surgical limb during landing which is consistent with previous research [12,23,37]. This is often thought to be a protective compensation while the surgical knee is still recovering. We also found that the surgical limb had higher values for ankle inversion, ankle adduction and hip rotation moment compared to the contralateral limb in both the landing and takeoff phases. Increased hip internal rotation angles are one of the main components of dynamic limb valgus which has been well documented as a risk factor for initial and subsequent ACL tears [3,11,21]. However, contrary to other research which has shown increased knee abduction moment as a risk factor for ACL injury, we found increased knee adduction moments on the surgical limb. This could indicate that these subjects have further protective offloading of their surgical knee which is seen clinically and has been documented in previous research, highlighting the importance of training the patient to appropriately and symmetrically load the knees in rehabilitation following ACLR [38,39]. In addition, this persistent offloading of the surgical limb shifts the load and increases the demand on the contralateral side, leading to potential overloading and contributing to the high rate of contralateral injuries following an initial ACL tear [9]. As this was not the focus of our paper, this finding deserves further investigation such as separating the groups into male and female subjects to examine if there is a sex difference or including strength or electromyography data to further examine clinical rehabilitation measures.

An avoidance of active shock absorption may suggest that the patient continues to be apprehensive and protecting the reconstructed knee or does not have adequate strength to eccentrically control their landing. Consistent with previous research, we also found asymmetries for ankle and knee flexion moments during the landing phase for the surgical limb compared to the contralateral limb [23,26,40,41]. This reduced knee flexion moment further contributes to decreased shock absorption upon landing and can cause the knee to be more at risk to reinjury since the joint experiences more shear stress and resultant ACL tears when it is in a more extended position [19]. In addition, research has shown that in this

timeframe following ACLR patients with patella or quadriceps tendon grafts have more sagittal plane deficits and slower recovery of symmetry than those with hamstring tendon grafts [19]. Disruption of the knee extensor mechanism and eccentric knee flexion control of the knee could be a factor in decreased knee flexion moments seen in these patients. Increasing active shock absorption during landing tasks is an important component of rehabilitation and return to sport training following an ACL tear to decrease the chance of reinjury and osteoarthritis development of the surgically reconstructed knee and maximize performance of athletic tasks.

We also found that patients had decreased energy generation on the surgical limb during takeoff illustrating that offloading strategies persist in this phase of the VDJ task. While asymmetries carry over from landing to takeoff, the magnitude of asymmetry of energy transfer appears to be attenuated during takeoff. If not properly addressed during rehabilitation, offloading strategies and compensations can persist leading to weakness on the ACLR limb and can also increase patients' long-term risk for OA in the reconstructed knee by hindering normal cartilage production [33,34,42]. This persistent weakness can also lead to reduced performance and may contribute to some patients stating they do not achieve their preinjury level of play. The resolution of avoidance strategies and the resulting improved lower extremity symmetry as a criterion for return to sport clearance could produce a sounder assessment and a more confident return to sport decision and reduce the risk of subsequent ACL injuries to the ipsilateral and contralateral side. The specific metrics of these strategies can be captured with motion analysis and shows the importance of this type of assessment in a clinical setting [19].

Previous research has typically used the takeoff phase of the VDJ tasks as a performance metric based off either jump height or flight time [27,28,43]. We found that jump height was significantly related to the power generation integral during takeoff at all joints. However, asymmetry of the power integral between limbs was not found to be related to jump height or performance of the task. Asymmetry may not have a large impact on an athlete's performance, and other research has shown that kinematic asymmetry has no effect on running efficiency or energy expenditure [44].

The limitations of our study include the retrospective design and limited sample size. Due to the relatively small sample size, the male and female participants were not analyzed separately, despite some evidence for biomechanical differences between the sexes [45]. The biomechanical model used a single segment foot and therefore did not model separate hindfoot and forefoot or midfoot motion. Following the common convention in motion analysis, we refer to the joint connecting the shank and foot as the ankle. In this context, ankle adduction is equivalent to ankle rotation in the transverse plane. Also, patients were between 6 to 10 months post-surgery and were not yet cleared for return to sport, which may limit generalizability to other patient populations. Because the patients in this study had not yet been cleared to return to full activity at the time of testing, they would be expected to continue to improve over time in terms of lower extremity symmetry and deviations from normal landing and takeoff biomechanics [19].

5. Conclusions

Similar sagittal, frontal, and transverse plane asymmetries were present during both the landing and takeoff phases of the VDJ task. Because asymmetries are translated from the landing through the takeoff phase, specifically in energy absorption to generation, this may give early insight as to why some athletes do not return to their preinjury level of play and are at higher risk of sustaining a future ACL injury. Though we did not find a significant relationship between asymmetries and performance, we found that jump height was significantly related to power generation which will not be maximized if one side produces less than maximal output. Targeting asymmetry and focusing on both landing and takeoff mechanics during rehabilitation may help to decrease the rate of injuries and maximize performance. Because premature return to sport may put athletes at an increased risk for future injury, further research is needed to establish more comprehensive,

objective return-to-sport criteria for adolescents post ACLR that can effectively show biomechanical deficits.

Author Contributions: The authors made the following contributions: Conceptualization, E.M.C. and N.M.M.; methodology, E.M.C., N.M.M. and T.A.L.W.; validation, N.M.M. and T.A.L.W.; formal analysis, N.M.M. and T.A.L.W.; investigation, M.J.K.; resources, C.D.V. and J.L.P.; data curation, E.M.C., N.M.M. and T.A.L.W.; writing—original draft preparation, E.M.C.; writing—review and editing, E.M.C., N.M.M., M.J.K., C.D.V., J.L.P. and T.A.L.W.; visualization, E.M.C., N.M.M. and T.A.L.W.; supervision, N.M.M. and T.A.L.W.; project administration, E.M.C., N.M.M. and T.A.L.W. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board (or Ethics Committee) of Children’s Hospital Los Angeles (protocol code #CHLA-14-00194 and 6/11/2014 of approval).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data is contained within the article.

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Conflicts of Interest: One author is a consultant for Arthex and Ceterix; neither company was involved in any aspect of this study. The remaining authors have no conflicts of interest to declare.

References

1. LaBella, C.R.; Hennrikus, W.; Hewett, T.E. Anterior Cruciate Ligament Injuries: Diagnosis, Treatment, and Prevention. *Pediatrics* **2014**, *133*, e1437–e1450. [\[CrossRef\]](#)
2. Beck, N.A.; Lawrence, J.T.R.; Nordin, J.D.; DeFor, T.A.; Tompkins, M. ACL Tears in School-Aged Children and Adolescents Over 20 Years. *Pediatrics* **2017**, *139*, e20161877. [\[CrossRef\]](#)
3. Hewett, T.E.; Myer, G.D.; Ford, K.R.; Heidt, R.S.; Colosimo, A.J.; McLean, S.G.; Van den Bogert, A.J.; Paterno, M.V.; Succop, P. Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective Study. *Am. J. Sports Med.* **2005**, *33*, 492–501. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Leppänen, M.; Pasanen, K.; Krosshaug, T.; Kannus, P.; Vasankari, T.; Kujala, U.M.; Bahr, R.; Perttunen, J.; Parkkari, J. Sagittal Plane Hip, Knee, and Ankle Biomechanics and the Risk of Anterior Cruciate Ligament Injury: A Prospective Study. *Orthop. J. Sport. Med.* **2017**, *5*. [\[CrossRef\]](#)
5. Myer, G.D.; Paterno, M.V.; Ford, K.R.; Quatman, C.E.; Hewett, T.E. Rehabilitation After Anterior Cruciate Ligament Reconstruction: Criteria-Based Progression Through the Return-to-Sport Phase. *J. Orthop. Sport Phys. Ther.* **2006**, *36*, 385–402. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Lyman, S.; Koulouvaris, P.; Sherman, S.; Do, H.; Mandl, L.A.; Marx, R.G. Epidemiology of Anterior Cruciate Ligament Reconstruction. *J. Bone Jt. Surg. Am. Vol.* **2009**, *91*, 2321–2328. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Dunn, K.L.; Lam, K.C.; Valovich McLeod, T.C. Early Operative Versus Delayed or Nonoperative Treatment of Anterior Cruciate Ligament Injuries in Pediatric Patients. *J. Athl. Train.* **2016**, *51*, 425–427. [\[CrossRef\]](#)
8. McCullough, K.A.; Phelps, K.D.; Spindler, K.P.; Matava, M.J.; Dunn, W.R.; Parker, R.D.; MOON Group; Reinke, E.K. Return to High School- and College-Level Football After Anterior Cruciate Ligament Reconstruction. *Am. J. Sports Med.* **2012**, *40*, 2523–2529. [\[CrossRef\]](#)
9. Wiggins, A.J.; Grandhi, R.K.; Schneider, D.K.; Stanfield, D.; Webster, K.E.; Myer, G.D. Risk of Secondary Injury in Younger Athletes After Anterior Cruciate Ligament Reconstruction. *Am. J. Sports Med.* **2016**, *44*, 1861–1876. [\[CrossRef\]](#)
10. Simon, D.; Mascarenhas, R.; Saltzman, B.M.; Rollins, M.; Bach, B.R.; MacDonald, P. The Relationship between Anterior Cruciate Ligament Injury and Osteoarthritis of the Knee. *Adv. Orthop.* **2015**, *2015*, 928301. [\[CrossRef\]](#)
11. Krosshaug, T.; Steffen, K.; Kristianslund, E.; Nilstad, A.; Mok, K.-M.; Myklebust, G.; Andersen, T.E.; Holme, I.; Engebretsen, L.; Bahr, R. The Vertical Drop Jump Is a Poor Screening Test for ACL Injuries in Female Elite Soccer and Handball Players. *Am. J. Sports Med.* **2016**, *44*, 874–883. [\[CrossRef\]](#)
12. Meyer, C.A.G.; Gette, P.; Mouton, C.; Seil, R.; Theisen, D. Side-to-side asymmetries in landing mechanics from a drop vertical jump test are not related to asymmetries in knee joint laxity following anterior cruciate ligament reconstruction. *Knee Surg. Sport Traumatol. Arthrosc.* **2018**, *26*, 381–390. [\[CrossRef\]](#)
13. Myer, G.D.; Martin, L.; Ford, K.R.; Paterno, M.V.; Schmitt, L.C.; Heidt, R.S.; Colosimo, A.; Hewett, T.E. No Association of Time From Surgery with Functional Deficits in Athletes After Anterior Cruciate Ligament Reconstruction. *Am. J. Sports Med.* **2012**, *40*, 2256–2263. [\[CrossRef\]](#)
14. Ardern, C.L.; Webster, K.E.; Taylor, N.F.; Feller, J.A. Return to sport following anterior cruciate ligament reconstruction surgery: A systematic review and meta-analysis of the state of play. *Br. J. Sports Med.* **2011**, *45*, 596–606. [\[CrossRef\]](#) [\[PubMed\]](#)

15. Müller, U.; Krüger-Franke, M.; Schmidt, M.; Rosemeyer, B. Predictive parameters for return to pre-injury level of sport 6 months following anterior cruciate ligament reconstruction surgery. *Knee Surg. Sport Traumatol. Arthrosc.* **2015**, *23*, 3623–3631. [[CrossRef](#)] [[PubMed](#)]
16. Schmitt, L.C.; Paterno, M.V.; Ford, K.R.; Myer, G.D.; Hewett, T.E. Strength Asymmetry and Landing Mechanics at Return to Sport after Anterior Cruciate Ligament Reconstruction. *Med. Sci. Sport Exerc.* **2015**, *47*, 1426–1434. [[CrossRef](#)]
17. Minetti, A.E.; Ardigo, L.P.; Susta, D.C. Using leg muscles as shock absorbers: Theoretical predictions and experimental results of drop landing performance. *Ergonomics* **1998**, *41*, 1771–1791. [[CrossRef](#)] [[PubMed](#)]
18. Mueske, N.; Katzel, M.J.; Chadwick, K.P.; VandenBerg, C.; Pace, J.L.; Zaslow, T.; Edison, B.; O'Callahan, B.G.; Nakata, H.L.; Wren, T. Biomechanical Symmetry During Drop Jump and Single-leg Hop Landing in Uninjured Adolescent Athletes. *Orthop. J. Sport Med.* **2019**, *7*. [[CrossRef](#)]
19. Mueske, N.M.; VandenBerg, C.D.; Pace, J.L.; Katzel, M.J.; Zaslow, T.L.; Padilla, R.A.; Wren, T.A. Comparison of drop jump landing biomechanics and asymmetry among adolescents with hamstring, patellar and quadriceps tendon autografts for anterior cruciate ligament reconstruction. *Knee* **2018**, *25*, 1065–1073. [[CrossRef](#)]
20. Renstrom, P.; Ljungqvist, A.; Arendt, E.; Beynon, B.; Fukubayashi, T.; Garrett, W.; Georgoulis, T.; Hewett, T.E.; Johnson, R.; Krosshaug, T.; et al. Non-contact ACL injuries in female athletes: An International Olympic Committee current concepts statement. *Br. J. Sports Med.* **2008**, *42*, 394–412. [[CrossRef](#)]
21. Boden, B.P.; Dean, G.S.; Feagin, J.A., Jr.; Garrett, W.E., Jr. Mechanisms of Anterior Cruciate Ligament Injury. *Orthopedics* **2000**, *23*, 573–578. [[CrossRef](#)]
22. Paterno, M.V.; Schmitt, L.C.; Ford, K.R.; Rauh, M.J.; Myer, G.D.; Hewett, T.E. Effects of Sex on Compensatory Landing Strategies Upon Return to Sport After Anterior Cruciate Ligament Reconstruction. *J. Orthop. Sport Phys. Ther.* **2011**, *41*, 553–559. [[CrossRef](#)]
23. Mueske, N.M.; Patel, A.R.; Pace, J.L.; Zaslow, T.L.; VandenBerg, C.D.; Katzel, M.J.; Edison, B.R.; Wren, T.A. Improvements in landing biomechanics following anterior cruciate ligament reconstruction in adolescent athletes. *Sport Biomech.* **2018**, *19*, 738–749. [[CrossRef](#)]
24. Leppänen, M.; Pasanen, K.; Kujala, U.M.; Vasankari, T.; Kannus, P.; Äyrämö, S.; Krosshaug, T.; Bahr, R.; Avela, J.; Perttunen, J.; et al. Stiff Landings Are Associated With Increased ACL Injury Risk in Young Female Basketball and Floorball Players. *Am. J. Sports Med.* **2017**, *45*, 386–393. [[CrossRef](#)]
25. Boden, B.P.; Sheehan, F.T.; Torg, J.S.; Hewett, T.E. Noncontact Anterior Cruciate Ligament Injuries: Mechanisms and Risk Factors. *Am. Acad. Orthop. Surg.* **2010**, *18*, 520–527. [[CrossRef](#)]
26. Hughes, G.; Musco, P.; Caine, S.; Howe, L. Lower Limb Asymmetry After Anterior Cruciate Ligament Reconstruction in Adolescent Athletes: A Systematic Review and Meta-Analysis. *J. Athl. Train.* **2020**, *55*, 811–825. [[CrossRef](#)] [[PubMed](#)]
27. Ford, K.R.; Myer, G.D.; Smith, R.L.; Byrnes, R.N.; Dopirak, S.E.; Hewett, T.E. Use of an Overhead Goal Alters Vertical Jump Performance and Biomechanics. *J. Strength Cond. Res.* **2005**, *19*, 394. [[CrossRef](#)]
28. Ford, K.; Myer, G.; Brent, J.; Hewett, T. Hip and knee extensor moments predict vertical jump height in adolescent girls. *J. Strength Cond. Res.* **2009**, *23*, 1327. [[CrossRef](#)] [[PubMed](#)]
29. Department of Health and Human Services. *Body Mass Index: Considerations for Practitioner*; Department of Health and Human Services Center for Disease Control and Prevention: Atlanta, GA, USA, 2014; pp. 1–4.
30. Wren, T.A.L.; O'Callahan, B.; Katzel, M.J.; Zaslow, T.L.; Edison, B.R.; VandenBerg, C.D.; Conrad-Forrest, A.; Mueske, N.M. Movement variability in pre-teen and teenage athletes performing sports related tasks. *Gait Posture* **2020**, *80*, 228–233. [[CrossRef](#)] [[PubMed](#)]
31. Linthorne, N.P. Analysis of standing vertical jumps using a force platform. *Am. J. Phys.* **2001**, *69*, 1198–1204. [[CrossRef](#)]
32. Dai, B.; Butler, R.J.; Garrett, W.E.; Queen, R.M. Using ground reaction force to predict knee kinetic asymmetry following anterior cruciate ligament reconstruction. *Scand. J. Med. Sci. Sports* **2014**, *24*, 974–981. [[CrossRef](#)]
33. Englund, M. The role of biomechanics in the initiation and progression of OA of the knee. In *Best Practice and Research: Clinical Rheumatology*; Elsevier Ltd.: Amsterdam, The Netherlands, 2010; Volume 24, pp. 39–46. [[CrossRef](#)]
34. Øiestad, B.E.; Holm, I.; Aune, A.K.; Gunderson, R.; Myklebust, G.; Engebretsen, L.; Aarsland Fosdahl, M.; Risberg, M.A. Knee Function and Prevalence of Knee Osteoarthritis after Anterior Cruciate Ligament Reconstruction. *Am. J. Sports Med.* **2010**, *38*, 2201–2210. [[CrossRef](#)]
35. Delahunt, E.; Sweeney, L.; Chawke, M.; Kelleher, J.; Murphy, K.; Patterson, M.; Prendiville, A. Lower limb kinematic alterations during drop vertical jumps in female athletes who have undergone anterior cruciate ligament reconstruction. *J. Orthop. Res.* **2012**, *30*, 72–78. [[CrossRef](#)]
36. Decker, M.J.; Torry, M.R.; Wyland, D.J.; Sterett, W.I.; Richard Steadman, J. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin. Biomech.* **2003**, *18*, 662–669. [[CrossRef](#)]
37. Renner, K.E.; Franck, C.T.; Miller, T.K.; Queen, R.M. Limb asymmetry during recovery from anterior cruciate ligament reconstruction. *J. Orthop. Res.* **2018**, *36*, 1887–1893. [[CrossRef](#)] [[PubMed](#)]
38. Pratt, K.A.; Sigward, S.M. Knee Loading Deficits During Dynamic Tasks in Individuals Following Anterior Cruciate Ligament Reconstruction. *J. Orthop. Sport Phys. Ther.* **2017**, *47*. [[CrossRef](#)] [[PubMed](#)]
39. Sigward, S.M.; Chan, M.S.M.; Lin, P.E.; Almansouri, S.Y.; Pratt, K.A. Compensatory strategies that reduce knee extensor demand during a bilateral squat change from 3 to 5 months following anterior cruciate ligament reconstruction. *J. Orthop. Sports Phys. Ther.* **2018**, *48*, 713–718. [[CrossRef](#)] [[PubMed](#)]

40. Wren, T.A.L.; Mueske, N.M.; Brophy, C.H.; Pace, J.L.; Katzel, M.J.; Edison, B.R.; Vandenberg, C.D.; Zaslow, T.L. Hop Distance Symmetry Does Not Indicate Normal Landing Biomechanics in Adolescent Athletes With Recent Anterior Cruciate Ligament Reconstruction. *J. Orthop. Sport Phys. Ther.* **2018**, *48*, 622–629. [[CrossRef](#)]
41. Lepley, A.S.; Kuenze, C.M. Hip and Knee Kinematics and Kinetics During Landing Tasks After Anterior Cruciate Ligament Reconstruction: A Systematic Review and Meta-Analysis. *J. Athl. Train.* **2018**, *53*, 144–159. [[CrossRef](#)]
42. Chmielewski, T.L. Asymmetrical Lower Extremity Loading After ACL Reconstruction: More Than Meets the Eye. *J. Orthop. Sport Phys. Ther.* **2011**, *41*, 374–376. [[CrossRef](#)]
43. Young, W.; Pryor, J.; Wilson, G. Effect of instructions on characteristics of countermovement and drop jump performance. *J. Strength Cond. Res.* **1995**, *9*, 232–236.
44. Seminati, E.; Nardello, F.; Zamparo, P.; Ardigò, L.P.; Faccioli, N.; Minetti, A.E. Anatomically Asymmetrical Runners Move More Asymmetrically at the Same Metabolic Cost. Carrier D, editor. *PLoS ONE* **2013**, *8*, e74134. [[CrossRef](#)] [[PubMed](#)]
45. Hewett, T.E.; Myer, G.D.; Ford, K.R. Anterior Cruciate Ligament Injuries in Female Athletes. *Am. J. Sports Med.* **2006**, *34*, 299–311. [[CrossRef](#)] [[PubMed](#)]