

Original Research

# Kinetic Asymmetry During a Repetitive Tuck Jump Task in Athletes with a History of Anterior Cruciate Ligament Reconstruction

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### Background

Athletes who have undergone anterior cruciate ligament reconstruction typically exhibit relatively high/rapid loading of their uninjured limb during bilateral landing and jumping (vs. their limb that underwent reconstruction), which may place their uninjured limb at risk for injury. However, previous studies have only examined forces and loading rates for tasks involving an isolated land-and-jump.

### Purpose

The purpose of this study was to examine bilateral landing and jumping kinetics during performance of a repetitive tuck jump task in athletes who had undergone anterior cruciate ligament reconstruction and completed rehabilitation.

### Study Design

Cross-sectional study

### Methods

Nine athletes (four males, five females) participated in this study. All participants had undergone successful unilateral anterior cruciate ligament reconstruction, had completed post-operative rehabilitation, and were in the process of completing return-to-sport testing. Athletes performed a repetitive tuck jump task for 10 seconds, while ground reaction forces were recorded for their uninjured and injured limbs via separate force platforms. Two-way analysis of variance, for within-subjects factors of limb and cycle, was performed for the impact forces, loading rates, and propulsive forces from the first five land-and-jump cycles completed.

### Results

There was not a limb-by-cycle interaction effect or main effect of cycle for the impact forces, loading rates, or propulsive forces; however, there was a main effect of limb for the impact forces ( $F(1, 8) = 14.64$ ;  $p=0.005$ ), loading rates ( $F(1, 8) = 5.60$ ;  $p=0.046$ ), and propulsive forces ( $F(1, 8) = 10.38$ ;  $p=0.012$ ). Impact forces, loading rates, and propulsive forces were higher for the uninjured limb, compared to the injured limb, over the five land-and-jump cycles analyzed.

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## Conclusion

The athletes in this study consistently applied higher and more rapid loads to their uninvolved limb over multiple land-and-jump cycles. This may help to explain the relatively high injury rates for the uninvolved limb in athletes who have returned to sport following anterior cruciate ligament reconstruction.

## INTRODUCTION

Anterior cruciate ligament (ACL) tears are common among young athletes who compete in sports that involved frequent landing and jumping, such as basketball.<sup>1</sup> Surgical reconstruction of the ACL is commonly recommended for athletes who plan to resume sports participation.<sup>2</sup> Unfortunately, athletes who have undergone ACL reconstruction are at relatively high risk for sustaining another ACL injury after returning to sport (compared to athletes without a history of ACL injury).<sup>3</sup> In most cases the second ACL injury occurs during the first year following return to sport and involves the athlete's previously uninjured limb (i.e. contralateral to the limb that underwent ACL reconstruction).<sup>4</sup> It appears there is an urgent need to identify factors that contribute to secondary risk of ACL injury (uninjured limb) in athletes who return to sport following ACL reconstruction.

Athletes often exhibit inter-limb asymmetries in limb loading during bilateral landing and jumping, even after they have completed rehabilitation and returned to sport.<sup>5-11</sup> Typically, athletes apply higher and more rapid loads to their uninvolved limb during landing and jumping, compared to their ACL-reconstructed limb. For example, Paterno et al.<sup>7</sup> examined vertical ground reaction forces during performance of a drop vertical jump task in a group of 14 athletes who had undergone ACL reconstruction, completed rehabilitation, and been cleared to return to sport by their physician and physical therapist, and found that the athletes in their study demonstrated higher peak vertical ground reaction forces for their uninvolved limbs (vs. their involved limbs) during the initial landing phase of the drop vertical jump (impact forces) and immediately prior to take-off (propulsive forces). In addition, they also demonstrated higher loading rates for their uninvolved limbs during landing. These inter-limb kinetic asymmetries may help to explain why ACL injuries are common for the uninvolved limb in athletes who have undergone ACL reconstruction, as relatively high/rapid impact forces contribute to a movement pattern that strains the ACL<sup>12</sup> and may increase ACL injury risk.<sup>13,14</sup>

While previous authors have found that athletes who have undergone ACL reconstruction tend to exhibit higher and more rapid loading of their uninvolved limb during bilateral landing and jumping, these studies have only included tasks that involve a single land-and-jump. As a result, it is unclear whether inter-limb asymmetry in limb loading changes as athletes complete multiple land-and-jump cycles. This is important to examine since athletes must often perform a series of landing-and-jumping cycles in short succession during competition. For instance, a basketball player pursuing a rebound may need to land and quickly jump, repeatedly. Athletes also often complete multiple land-and-jump cycles during plyometric training (e.g.

repeated tuck jumps).<sup>15,16</sup> In addition, previous studies have not examined symmetry in foot initial contact timing during performance of a repetitive jump-landing task. Examining foot initial contact timing could provide additional insight, since the limbs are loaded very rapidly during landing, and therefore, even subtle asymmetries in initial contact timing could contribute to an overreliance on one limb for support.<sup>16</sup>

The purpose of this study was to examine bilateral landing and jumping kinetics during performance of a repetitive tuck jump task in athletes who had undergone ACL reconstruction and completed rehabilitation. It was hypothesized that athletes would demonstrate higher impact forces, loading rates, and propulsive forces for their uninvolved limb, compared to their involved limb, for each land-and-jump cycle analyzed. No *a priori* hypotheses were proposed regarding how the degree of inter-limb asymmetry would change as athletes completed successive land-and-jump cycles, since previous studies have not examined changes in limb loading across multiple jump-landings. A secondary purpose of this study was to examine foot initial contact timing during performance of the repetitive tuck jump task, as this could provide additional insight into why athletes who have undergone ACL reconstruction tend to exhibit greater loading of their uninjured limb during landing.

## METHODS

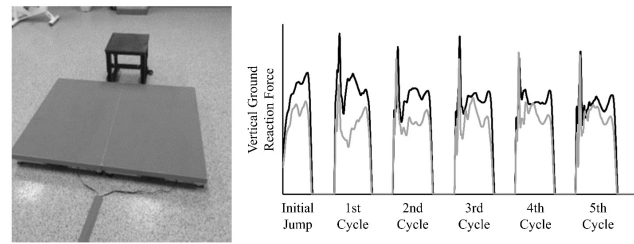
Nine athletes (four males, five females) participated in this cross-sectional study. All data were collected during the athlete's return to sport testing session, which took place at the Academy of Sports and Health Centre (Fort Wayne, IN, USA). Athletes were eligible to participate if they were between 14-25 years of age, had undergone successful unilateral primary ACL reconstruction within the previous 18 months, intended to return to a sport that involved landing/jumping, had completed conventional post-operative rehabilitation, and had been cleared by their physician and physical therapist to resume landing and jumping activities. Athletes who were 14-25 years of age were selected for this study because this appears to be the age range where most ACL injuries occur<sup>17</sup> and the risk of a second ACL injury appears to be particularly high in athletes 25 years of age or younger.<sup>3</sup> Athletes were excluded from participating if they had a history of surgery or significant injury involving their uninvolved limb. All athletes had isolated ACL injuries, with no other concomitant injuries. The mean ( $\pm$  standard deviation) age, mass, and height of the athletes were  $16.9 \pm 1.8$  years,  $70.3 \pm 12.4$  kg, and  $1.8 \pm 0.1$  m. The median (range) number of days since their ACL reconstruction surgery was 175 days (152-223 days). Six athletes had received bone-patellar tendon-bone autografts and three had received hamstrings tendon autografts. Five athletes reported that they had injured their dominant limb, while

four athletes reported that they had injured their non-dominant limb. For the purpose of this study, the dominant limb was defined as the leg the athletes reported that they would have used to kick a ball for maximal distance prior to their injury. This study protocol was approved by the Institutional Review Board at Lutheran Hospital (Fort Wayne, IN, USA). All athletes provided informed consent/assent prior to enrollment and informed consent was obtained from a parent or guardian for athletes who were younger than 18 years of age.

Athletes completed the Sport and Recreation subscale of the Knee Injury and Osteoarthritis Outcome Score (KOOS) questionnaire prior to testing.<sup>18</sup> The Sport and Recreation subscale of the KOOS asks individuals to rate their perceived level of difficulty with squatting, running, jumping, twisting/pivoting, and kneeling on a Likert scale (none, mild, moderate, severe, extreme) and values are transformed into a percentage where 0% represents extreme difficulty and 100% represents no deficits in knee-related function. The Sport and Recreation subscale of the KOOS has been shown to demonstrate good test-retest reliability in individuals with a history of ACL injury (intraclass correlation coefficient = 0.81) and is responsive to changes in knee-related function following ACL reconstruction.<sup>18</sup> This self-reported measure was recorded in order to describe the athletes' perceived level of knee-related function.

Next, athletes completed a standardized warm-up that included various landing and jumping tasks. They then completed the repetitive tuck jump task described by Myer et al.<sup>16</sup> Athletes started in a standing position with their feet on separate, adjacent force platforms (AccuPower, Advanced Mechanical Technology, Inc., Watertown, MA, USA) (Figure 1). They initiated the tuck jump task by performing a rapid countermovement, jumped vertically bringing their knees upward until their thighs were parallel to the ground (tuck jump), and then landed on both limbs. Upon landing, they immediately performed the next tuck jump as quickly as possible. The athletes continued to perform tuck jumps for 10 seconds. The force platforms simultaneously recorded three-dimensional ground reaction forces at a sampling rate of 600 Hz throughout performance of the repetitive tuck jump task. Athletes were encouraged to focus on jumping vertically during the task so that their feet continued to contact the same force platforms. An investigator monitored the locations of the athletes' feet during the landings and noted when an athlete's foot did not appear to land completely within the respective force platform. Each athlete was given a demonstration and performed a limited practice trial prior to testing.

Ground reaction force data were filtered using a 4th order, zero lag, low-pass Butterworth filter with a cutoff frequency of 50 Hz and normalized to body weight (BW).<sup>7</sup> The peak vertical ground reaction forces (impact forces) and loading rates during the initial 25% of stance and the peak vertical ground reaction forces during last 25% of stance (propulsive forces) were identified from the time series associated with each force platform during the first five land-and-jump cycles of the repetitive tuck jump task (Figure 1). All athletes successfully landed with their feet on separate force platforms for the first five land-and-jump cycles. Additional land-and-jump cycles beyond the first five were not



**Figure 1.**

Left panel - picture of the dual force platform setup. Right panel - example of one athlete's vertical ground reaction force time series during performance of the repetitive tuck jump task (uninjured limb = black time series; injured limb = grey time series).

examined since many athletes failed to continue to land with their feet on separate force platforms. The stance phase was defined as the total time when the vertical ground reaction force exceeded a threshold of 10 N (i.e. initial contact to takeoff). Loading rates were calculated by dividing the impact forces by the time from initial contact until the impact force (BW/s).<sup>7</sup> Inter-limb symmetry indices were also calculated for the impact forces, loading rates, and propulsive forces for each land-and-jump cycle by dividing the values for the involved limb by those of the uninjured limb, and multiplying by 100.<sup>8</sup> As a result, inter-limb symmetry index values less than 100% reflect lower or less rapid loading of the involved limb.

In order to examine initial contact timing during the landings, the first frame where the vertical ground reaction force exceeded 10 N (initial contact) and remained greater than 10 N for at least 50 frames was identified. The difference between the initial contact frames for each limb (uninvolved, involved) was then converted to milliseconds (ms) based on the sampling rate of the force platforms.<sup>19,20</sup> Calculations were performed so that positive values represented earlier initial contact for the uninvolved limb, negative values represented earlier initial contact for the involved limb, and zero values represented simultaneous initial contact. Unfiltered ground reaction force data were used for examining the initial contact timing,<sup>19</sup> since filtering can result in inaccurate temporal events, especially when there is a rapid change in signal amplitude.<sup>21</sup> All data processing was completed using custom MATLAB scripts (MathWorks Inc., Natick, MA, USA).

## STATISTICAL ANALYSIS

Two-way analysis of variance for within-subjects factors of 'limb' (uninvolved, involved) and 'cycle' (1st, 2nd, 3rd, 4th, 5th land-and-jump cycle) were performed for the impact forces, loading rates, and propulsive forces. Main effects of limb and cycle were examined when there was not a significant limb-by-cycle interaction effect. A repeated measures analysis of variance, for a within-subjects factor of cycle, was conducted to examine initial contact timing differences among the landings. An alpha of .05 was used for all statistical tests. SPSS software was used for statistical analysis (Version 27; IBM Corp., Armonk, NY, USA). 95% confidence intervals (95% CI) were calculated for the initial contact

**Table 1. Impact forces, loading rates, and propulsive forces for the uninvolved limb (Uninv) and ACL-reconstructed (involved) limb (ACLR) for the first five land-and-jump cycles of the repetitive tuck jump task.**

	1st Cycle		2nd Cycle		3rd Cycle		4th Cycle		5th Cycle	
	Uninv	ACLR	Uninv	ACLR	Uninv	ACLR	Uninv	ACLR	Uninv	ACLR
Impact Forces (BW)	1.98 ±0.41	1.55 ±0.25	2.17 ±0.63	1.53 ±0.34	2.07 ±0.50	1.69 ±0.35	2.13 ±0.62	1.65 ±0.37	1.95 ±0.40	1.68 ±0.39
Loading Rates (BW/s)	29.61 ±9.17	22.98 ±7.40	33.74 ±12.92	23.91 ±7.45	31.47 ±11.86	26.25 ±7.44	32.00 ±12.38	28.76 ±12.17	28.89 ±10.34	27.34 ±14.44
Propulsive Forces (BW)	2.01 ±0.72	1.63 ±0.58	2.05 ±0.85	1.63 ±0.62	1.88 ±0.75	1.70 ±0.64	2.10 ±0.87	1.68 ±0.56	2.01 ±0.75	1.79 ±0.78

Mean ± standard deviation impact forces, loading rates, and propulsive forces for each landing. Uninv = uninvolved limb; ACLR = ACL-reconstructed (involved) limb; BW = bodyweight; BW/s = bodyweight/second

**Table 2. Impact force, loading rate, and propulsive force inter-limb symmetry indices for the first five land-and-jump cycles of the repetitive tuck jump task.**

	1st Cycle	2nd Cycle	3rd Cycle	4th Cycle	5th Cycle
Impact Force Inter-Limb Symmetry Index (%)	80.10 ±14.56	76.52 ±28.28	83.60 ±15.89	80.91 ±19.76	86.81 ±11.81
Loading Rate Inter-Limb Symmetry Index (%)	79.00 ±14.25	79.41 ±36.01	88.96 ±20.70	96.00 ±38.11	93.32 ±25.72
Propulsive Forces Inter-Limb Symmetry Index (%)	81.60 ±9.40	83.83 ±20.25	94.04 ±24.67	83.91 ±13.77	88.03 ±12.08

Mean ± standard deviation impact force, loading rate, and propulsive force inter-limb symmetry indices for each land-and-jump cycle analyzed. Symmetry index values less than 100% reflect higher or more rapid loading of the uninvolved limb, compared to the involved limb.

**Table 3. Initial contact timing differences for the first five landings of the repetitive tuck jump task.**

	1st Cycle	2nd Cycle	3rd Cycle	4th Cycle	5th Cycle
Time (ms)	4.4 ± 7.5 (-1.4, 10.2)	5.0 ± 12.1 (-4.3, 14.3)	6.5 ± 14.2 (-4.4, 17.4)	6.1 ± 16.0 (-6.2, 18.4)	5.6 ± 14.7 (-5.7, 16.9)

Mean ± standard deviation and 95% confidence interval (lower bound, upper bound) for the initial contact timing differences for each landing analyzed. Positive values indicate that the uninvolved limb made contact prior to the involved limb. ms = milliseconds.

timing differences.

## RESULTS

The mean (range) score on the Sport and Recreation subscale of the KOOS questionnaire was 90.0% (80-100%).

For the impact forces, there was not a limb-by-cycle interaction effect ( $F(4, 32) = 1.14$ ;  $p=0.355$ ) or main effect of cycle ( $F(4, 32) = 0.45$ ;  $p=0.770$ ); however, there was a main effect of limb ( $F(1, 8) = 14.64$ ;  $p=0.005$ ). Impact forces were higher for the uninvolved limb across all five landings analyzed (Tables 1 & 2).

For the loading rates, there was not a limb-by-cycle interaction effect ( $F(4, 32) = 1.60$ ;  $p=0.198$ ) or main effect of cycle ( $F(4, 32) = 0.86$ ;  $p=0.501$ ); however, there was a main

effect of limb ( $F(1, 8) = 5.60$ ;  $p=0.046$ ). Loading rates were higher for the uninvolved limb across all five landings analyzed (Tables 1 & 2).

For the propulsive forces, there was not a limb-by-cycle interaction effect ( $F(4, 32) = 1.02$ ;  $p=0.412$ ) or main effect of cycle ( $F(4, 32) = 0.35$ ;  $p=0.839$ ); however, there was a main effect of limb ( $F(1, 8) = 10.38$ ;  $p=0.012$ ). Propulsive forces were higher for the uninvolved limb across all five land-and-jump cycles analyzed (Tables 1 & 2).

The repeated measures analysis of variance indicated that there was no difference in initial contact timing among the five landings ( $F(4, 32) = 0.062$ ;  $p=0.993$ ) (Table 3).

## DISCUSSION

The primary purpose of this study was to examine bilateral landing and jumping kinetics during performance of a repetitive tuck jump task in athletes who had undergone ACL reconstruction and completed rehabilitation. As hypothesized, athletes demonstrated higher impact forces, loading rates, and propulsive forces for their uninvolved limb, compared to their involved limb, for each land-and-jump cycle analyzed (main effects of limb). The degree of inter-limb kinetic asymmetry did not change significantly across the five land-and-jump cycles (no limb-by-cycle interaction effects). As a result, it appears that the athletes maintained a fairly consistent level of inter-limb kinetic asymmetry when performing the repetitive tuck jump task. The results of this study build on those of earlier studies<sup>5-11</sup> that have identified persistent inter-limb kinetic asymmetry during performance of tasks involving a single land-and-jump in athletes who have undergone ACL reconstruction and may help to explain why ACL injuries are common for the uninvolved limb in athletes who return to sport following ACL reconstruction.

The athletes in this study exhibited inter-limb impact force differences ranging from 14.6-34.7% for the five successive land-and-jump cycles analyzed. In each instance, impact forces were greater for the uninvolved limb. This finding that athletes tend to offload their involved limb is consistent with previous studies that have examined isolated, double-leg landings in athletes post-ACL reconstruction.<sup>5-11</sup> Inter-limb symmetry in loading rates and propulsive forces have been less frequently examined in athletes who have undergone ACL reconstruction. However, Paterno et al.<sup>7</sup> reported that loading rates during the landing phase of a drop vertical jump were 45.4% higher for the uninvolved limb, compared to the involved limb, in a group of athletes who had undergone ACL reconstruction and been cleared to return to sport. In addition, they also reported that propulsive forces were 16.7% higher for the uninvolved limb. In general, there appears to be agreement among studies that the uninvolved limb tends to experience higher and more rapid loading following ACL reconstruction, during both single (previous studies)<sup>5-11</sup> and multiple jump land-and-jump cycles (the current study). This shift in loading toward the uninvolved limb likely places greater demands on the uninvolved knee, as asymmetries in ground reaction forces appear to correlate with asymmetries in knee loading.<sup>22,23</sup> In addition, previous studies have also found that athletes who have undergone ACL reconstruction demonstrate greater knee loading (e.g. increased knee extension moments) for their uninvolved limb during bilateral landing and jumping.<sup>6,10,11</sup> These persistent kinetic asymmetries may increase risk of a secondary ACL injury<sup>24</sup> and/or contribute to knee degenerative changes.<sup>11,25,26</sup> As a result, there appears to be a need to explore novel rehabilitation approaches that could potentially more effectively target these persistent kinetic asymmetries. For instance, providing visual feedback related to side-to-side differences in limb loading during movement performance may be particularly effective for promoting inter-limb kinetic symmetry and minimizing maladaptive changes in an athlete's movement pattern following ACL reconstruction.<sup>27</sup> It is also

important to continue to examine factors that contribute to inter-limb kinetic asymmetry following ACL reconstruction (e.g. fear of re-injury, strength deficits, motor pattern adaptations).<sup>10,28,29</sup>

Although not the primary purpose of this study, it is interesting that athletes tended to make earlier initial contact with their uninvolved limb during landing (based on the sign of the average initial contact timing differences). While it should be noted that the 95% CIs all included zero, on average, initial contact occurred 4.4-6.5 ms earlier for the uninvolved limb across the five landings analyzed. Ford et al.<sup>19</sup> examined initial contact limb preference during the initial landing phase of a drop vertical jump in 101 athletes who had undergone ACL reconstruction and found that 71.3% made initial contact first with their uninvolved limb. It appears that athletes who have undergone ACL reconstruction have a tendency to make initial contact with their uninvolved limb, prior to their involved limb, upon landing. Perhaps this reflects a movement strategy to reduce loading of the involved limb during bilateral landings.

The repetitive tuck jump task is a common plyometric training exercise for athletes.<sup>15</sup> The results of this study indicate that athletes who have undergone ACL reconstruction may consistently offload their involved limb when performing repeated tuck jumps. Physical therapists, athletic trainers, and strength and conditioning coaches should consider this when prescribing the repetitive tuck jump task for athletes with a history of ACL reconstruction, as consistently offloading the involved limb and placing greater loads on the uninvolved limb may contribute to the development, or further development, of inter-limb neuromuscular asymmetries.

Although the findings from this study make a valuable contribution to an important body of literature, the study limitations need to be acknowledged. First, only the initial five land-and-jump cycles of the repetitive tuck jump task were examined; inter-limb symmetry could change as athletes complete additional cycles. In addition, the tuck jump task may not reflect the type of repetitive landing and jumping routinely performed in sports such as basketball. In-shoe kinetic sensors<sup>30</sup> and inertial measurement units<sup>31</sup> offer opportunities to examine inter-limb kinetic symmetry during landing and jumping under more game-like conditions. This study also did not include a comparison group of uninjured athletes. However, previous studies have already determined that athletes who have undergone ACL reconstruction demonstrate greater inter-limb kinetic asymmetry compared to athletes without a history of ACL reconstruction.

## CONCLUSION

During performance of a repetitive tuck jump task, athletes who had undergone ACL reconstruction applied higher and more rapid loads to their uninvolved limb, compared to their involved limb. They also exhibited a tendency to make initial foot contact first with their uninvolved limb during landing. These inter-limb asymmetries may help to explain why athletes often sustain ACL injuries involving their previously uninjured limb upon returning to sport following ACL reconstruction.

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#### CONFLICTS OF INTEREST

The authors have no conflicts of interest to disclose.

#### DISCLOSURE

This study received no funding.

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