Title: The Utility of Functional Data Analyses to Reveal Between-Limb Asymmetries in Those With a History of ACLR

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Title: The Utility of Functional Data Analyses to Reveal Between-Limb Asymmetries in Those With a History of ACL Reconstruction

Abstract

Context: Researchers have traditionally used motion capture to quantify discrete biomechanical data points (peak values) during hop testing. However, these analyses provide a narrow view of movement as they restrict the evaluation to a single time point (i.e. certain percentage of stance). The application of more comprehensive analyses may identify important characteristics that are masked by discrete analyses often used to screen patients for activity. **Objective:** To examine the utility of functional data analyses to reveal asymmetries that are undetectable by discrete (i.e. single time point) evaluations in those with a history of anterior cruciate ligament reconstruction (ACLR) who achieve clinical hop symmetry. **Design:** Cross-sectional study. **Setting:** Laboratory. **Patients or Other Participants:** 15 subjects with unilateral ACLR (age=21±3yrs; time from surgery= 4±3yrs) and 15 healthy controls (age=23±2yrs) participated. **Intervention(s):** Lower extremity biomechanics were collected during the triple hop for distance task. **Main Outcome Measure(s):** Peak sagittal plane joint power, joint work, and power profiles were determined. **Results:** Discrete analyses identified significantly lower peak knee power and work in the ACLR limb compared to contralateral and control limbs ($p<0.05$), but were unable to identify differences at the ankle or hip. Functional data analyses identified significant asymmetries at the ankle, knee, and hip between ACLR and contralateral or control limbs throughout stance ($p<0.05$) and revealed that these asymmetries stemmed from knee power deficits that were prominent during early loading. **Conclusions:** Despite achieving hop distance symmetry, ACLR knees absorbed less power. While this information was revealed with the discrete (i.e. single time point) analyses, underlying asymmetries at the ankle and hip were masked. Functional data analyses identified inter-limb asymmetries at the ankle, knee, and hip throughout ground contact and more fully elucidate the extent and source of asymmetries that can be utilized by clinicians and researchers alike to guide clinical decision making.

Key Words: ACL, limb symmetry, kinetics

Key Point #1: Clinical (limb symmetry indices) and discrete (peak values) analyses fail to capture the full scope of asymmetry.

Key Point #2: Functional data analyses are able to more comprehensively evaluate movement quality by comparing between limb differences in both time and magnitude.

Key Point #3: Current clinical and research assessments can mask underlying movement strategies. Researchers should adapt more in depth analyses to fully capture asymmetry and direct evidence based practices used in clinical decision making.

INTRODUCTION

To protect athletes against recurrent injury, many clinicians employ a battery of tests that primarily rely on limb symmetry indices to assess functional movement at return to sport. However, the rate of reinjury,[1-3] persistent functional deficits,[4-7] and the failure to return athletes to their preinjury level of competition after anterior cruciate ligament reconstruction (ACLR)[8] suggests there is a need to 1) better understand the factors that contribute to inadequate recovery and 2) develop more comprehensive assessments of dynamic movement. Currently, as part of a battery of tests, many patients are evaluated through a series of functional hop tests[9-11] to determine whether or not the individual can hop as far on the ACLR limb as the contralateral limb. Individuals that achieve at least 90% distance of their contralateral limb are often deemed ready to transition back to sport.[10,12,13] However, using only hop distance to assess movement does not accurately capture all aspects of knee function.[14] Furthermore, the contralateral limb also experiences a decline in functionality suggesting a between-limb comparison may not be enough to release a patient to return to sport.

Researchers have proven this theory using biomechanical methods that often report kinematics and kinetics at discrete time points (e.g. peak values) during hop testing and have repeatedly shown that despite achieving hop distance symmetry, ACLR limbs exhibit lower peak knee flexion angle, peak knee extension moment, and peak knee power compared to contralateral and/or control limbs during single hop tasks.[6,14,15] While important, the discrete approach of evaluating peak values, only provides the researcher with a "snapshot" of how the joint in question is moving at one single time point (i.e. percentage of stance), and may overlook other important movement characteristics. Further, discrete analyses most often only evaluate the knee and fail to consider the intricate combination of movement strategies utilized at the ankle, knee, and hip to complete the task. Analyzing characteristics of movement throughout the duration of the task (i.e. timing and magnitude of inter-limb differences) simultaneously to consider how a patient achieves limb symmetry may provide clinicians with additional knowledge regarding underlying asymmetries that are be masked by discrete analyses and may be barriers to reaching optimal recovery.[5,16]

Of broader significance, evidence based medicine requires the integration of the best scientific evidence with clinical expertise. It is our position that current clinical and research assessments are incomplete and can mask underlying movement strategies. Therefore the purpose of this study is to examine the utility of functional data analyses to reveal between limb asymmetries that are undetectable by discrete (i.e. single time point) evaluations in those with a history of ACLR who achieve clinical hop symmetry. To do this we assessed between limb differences in joint power and joint work in individuals post ACLR who achieve clinically acceptable levels of limb symmetry (>90% limb symmetry index [LSI]) on the triple hop for distance task. To further extend insight, a healthy control group was also included to reveal inherent asymmetries that are specific to those without a history of knee injury. We anticipate that compared to the discrete analyses that reveal the magnitude of difference from a snapshot of movement and often only consider the knee, performing functional data analyses at all lower extremity joints would 1) provide a more comprehensive evaluation of movement and 2) detect asymmetries masked by discrete analyses that allow individual's with a history of ACLR to achieve clinical limb symmetry. The application of a functional data analysis to the field is highly relevant, as that this type of data analyses can be adopted by researchers to provide clinicians with critical insight into currently disregarded movement asymmetries that can be targeted with concentrated rehabilitation efforts.

METHODS

This level 3 evidence retrospective cohort study was approved by the Institutional Review Board at the University of XXXX and informed consent was obtained from all subjects prior to data collection.

Patients

Fifteen patients who had previously undergone primary unilateral ACLR (age=21±3 yrs; time from surgery= 4±3 yrs) were recruited from the Department of Orthopaedic Surgery at the University of XXXX and participated in this study. To characterize healthy movement profiles during the triple hop, 15 healthy individuals (age=23±2 yrs) matched by age, height and weight, and activity level with no previous history of lower extremity surgery were also included. Additional patient demographics can be found in Table 1. All patients with history of ACLR had completed standard rehabilitation protocols and were cleared by their orthopaedic surgeon to return to unrestricted functional activities. All subjects (healthy controls or patients with history of ACLR) clinically passed the triple hop test with at least a 90% LSI, measured as hop test performance of the ACLR limb/contralateral limb × 100%. Subjects were excluded from the study if they had sustained previous knee surgery other than the current ACLR, a contralateral lower extremity injury within the past 6 months, were pregnant, had a cardiac pacemaker, were allergic to adhesives, or had any open skin lesions. The study was approved by the Institutional Review Board at the University of XXXX and informed consent was obtained from all subjects prior to data collection.

Procedures

A 12 camera motion capture system (Vicon, Oxford Metrics, London, England) synchronized with 2 force plates (Bertec Corp., Columbus, Ohio) was used to record kinematic and kinetic data recorded at 240 Hz and 1200 Hz, respectively. After the subjects height and mass were taken, they were instrumented with 37 retro-reflective markers as previously described.[17] The motion analysis system was calibrated and a static trial was collected to determine joint centers of rotation, define respective joint and segmental coordinate axes, and establish neutral alignment from which subsequent kinematic measures were referenced. Subjects were instructed to complete the triple hop for distance task as described by Noyes et al[10,18] in which bilateral lower extremity sagittal plane kinetics and kinematics were simultaneously captured. The triple hop for distance task was evaluated as it requires a high level of dynamic control and allows for the assessment of a subject's ability to produce, transfer, and absorb force consecutively through three hops. The triple hop task was performed bilaterally and the order of limb testing was randomized for each subject. Subjects were allowed two practice trials for each limb and data collection was concluded when three successful trials were attained for each limb. A trial was considered successful if the subject’s full foot landed on the force plate on the second of three hops and if they were able to maintain balance on only their take-off limb for at least one second during landing of the last hop. As only the second hop included force plate data, these trials were used in subsequent analyses. At most, 5 trials were required in order to attain 3 successful trials for each limb. Marker trajectories were exported to Visual3D software (C-Motion; Rockville, MD, USA) for processing. Kinematic and ground reaction force (GRF) data were filtered using a fourth order, zero-lag, low-pass Butterworth filter at a 12 Hz cut-off frequency[19]. A kinematic model that included eight skeletal segments (bilateral foot, shank and thigh segments, pelvis and trunk) and 27 degrees of freedom was created from the static trial. Hip, knee and ankle angles were determined using the default Cardan sequence method in Visual3D, X-Y-Z convention (flexion/extension, abduction/adduction, internal/external rotation). Data were normalized to 100% of stance. Stance was then separated into the eccentric (landing) phase (initial contact to peak dorsiflexion, knee flexion, and hip flexion) and the concentric (take-off) phase (peak dorsiflexion, knee flexion, and hip flexion to toe-off) to permit the independent analysis of the ankle, knee, and hip joint during each phase.[20] Joint moments were determined using a standard inverse dynamics approach and were normalized to body mass. Joint power was then calculated as the product of joint moment and angular velocity. Joint power was evaluated as it's reflective of energy generation, transfer, and absorption in which the triple hop task demands. Positive joint power reflected the concentric phase of energy generation and negative joint power reflected the eccentric phase of energy absorption. Joint work was determined by integrating the joint power curves with respect to time during the concentric and eccentric phases. As data were normalized to 100% of stance to allow for group comparisons, timing is considered to be relative. In the ACLR group, bilateral (ACLR and contralateral) limbs were analyzed. In the control group a representative limb, matched by which limb received ACLR, was analyzed. For instance, 53% of the ACLR group received surgery on their right limb so we assessed the right limb for 53% (8 out of 15) of the subjects in the control group[21,22] via random assignment.

Statistical Analyses

All data analyses were performed in RStudio (version 1.1.456) with an alpha level of $p<0.05$. Independent t-tests were performed to evaluate if there were differences in demographic variables between the ACLR and control group cohorts. For discrete analyses, the global average of the three successful trials were used for the analysis. Paired (ACLR and contralateral) and independent (ACLR and control) t-tests were performed to assess between limb differences in peak joint power and joint work (Table 2), and to assess the percent stance when peak power occurred in the eccentric and concentric phases of movement (Table 3). To extend the aforementioned discrete analyses and detect differences in joint power across all of stance, functional analyses of variance (FANOVA) were performed using the functional data analysis package in RStudio to compare 1) the ACLR limb to the contralateral limb and 2) the ACLR limb to the control limb. A benefit of the FANOVA is that it evaluates between group variances by identifying systematic differences between all trials of a group. This methodology enabled the inclusion of three trials per subject rather than using only a global average.[23] Significant between limb differences, calculated at each percent of stance, with the corresponding 95% confidence interval were plotted (Figures 1 and 2 B,D,F) alongside ensemble group averages (Figure 1 and 2 A,C,E). Inter-limb differences were considered statistically significant whenever the 95% confidence intervals did not overlap zero, indicating $p<0.05$.

RESULTS

No significant descriptive differences were found between groups (Table 1). To distinguish the eccentric and concentric phases of movement on a joint by joint basis, we used average peak dorsiflexion, knee flexion, and hip flexion angles as previously described.[20] For the ACLR, contralateral, and control limbs peak dorsiflexion, knee flexion, and hip flexion occurred at 63 ± 8 % , 50 ± 6 % and 24 ± 8 % of stance, respectively.

Discrete analyses

Using only discrete values, peak knee power of the ACLR limb was significantly lower than the contralateral limb during the eccentric phase ($p=0.017$, Table 2). The ACLR knee performed significantly less work than the contralateral knee during the eccentric phase ($p=0.001$), and the control knee during the concentric ($p=0.001$) and eccentric phases ($p=0.019$). Notably, the discrete approach did not identify any differences at the ankle or hip in joint power or work (Table 2). Additionally, this approach did not identify any differences in the percent stance where peak power occurred, i.e. no differences in the time of peak power were determined for any lower extremity joint (Table 3).

Functional Data Analysis

Results of the FANOVA between the ACLR and contralateral limbs for joint power are shown in Figure 1. Asymmetries between limbs were first observed by a decrease in eccentric power (energy absorption) by the ACLR knee between 7 and 16% of stance (Figure 1D; $p<0.05$).

This was followed by a significant increase in concentric power by the ACLR hip between 22 and 31% of stance (Figure 1F; p<0.05).

Results of the FANOVA between the ACLR and representative control limbs for joint power are shown in Figure 2. Significant asymmetries between limbs were found at the ankle, knee, and hip. Similarly to ACLR vs contralateral limbs, asymmetries between ACLR and control limbs were initiated by a significant decrease in eccentric power (energy absorption) by the ACLR knee between 3-11% of stance. This was immediately followed by an minimal but significant increase in power by the ACLR ankle and ACLR hip between 13-19% and 21-29% of stance, respectively. Significant differences at the ankle, knee and hip were persistent throughout the rest of stance and most prominently at the hip between 35-55% and 92-98% and the knee between 56-69% and 79-90% of stance (Figures 1 and 2).

DISCUSSION

We examined the utility of functional data analyses to reveal between limb asymmetries that are masked by discrete analyses in a cohort of ACLR and healthy individuals that achieved clinically acceptable levels of hop symmetry for the triple hop for distance task. The purpose was to use more comprehensive analyses to reveal characteristics (e.g. timing and magnitude) of the task that current, over simplified analyses do not consider but may be better indicators of function and the quality of movement than LSI's and discrete analyses. Of broader significance, this proof of concept study shows that a functional data analysis can be adopted by sports medicine researchers to provide clinicians with critical insight into inter-limb asymmetries not captured by current clinical and research assessments. These asymmetries may be contributors to suboptimal outcomes and thus, this evaluation strategy can be used to refine rehabilitation protocols.

In line with previous work,[5,15] discrete and functional data analyses revealed a significant decrease in peak knee power in the ACLR limb during eccentric landing that was not captured through clinical analyses (<90% LSI). To this point, others[24] have suggested that clinical metrics such as LSI's overestimate function through the failure to identify underlying biomechanical alterations and movement strategies during single limb hop tasks. Our findings provide direct evidence of this further confirming that passing 90% LSI criteria for hop distance does not equate to symmetry in biomechanical outcomes.

The only asymmetry detected using the discrete analyses was reduced knee power and work (see Table 2). The functional data analyses were able to extend this key insight by uncovering the magnitude of inter-limb asymmetries and the timing of stance when significant inter-limb asymmetries occurred. In the present study, this approach uniquely identified asymmetries at all lower extremity joints and the timing information revealed sequential joint compensations in the ACLR cohort that stemmed from the decrease energy absorption (i.e. decrease in power) at the ACLR knee early in loading. This is clinically important, as adequate energy absorption permits the dissipation of forces through eccentric muscle action. Without this adequacy, there is redistribution of energy and mechanical work, which in turn leads to abnormal loads at the knee. Given the previously established connection between abnormal joint loading and joint disease progression[25,26] and injury risk,[20] our findings of reduced joint power in the ACLR limb in early loading is of high importance. As a natural extension of this finding, it is recommended that clinicians consider the concentrated use of eccentric exercise in rehabilitation to mitigate this early landing asymmetry.[17] Future data using this rehabilitation approach with more comprehensive assessments of inter-limb asymmetries during dynamic tasks are needed to test this hypothesis. Moreover, future work is needed to establish the clinical meaningfulness of inter-limb asymmetries in order to better understand how they contribute to injury risk.

Our data suggest that more robust techniques for evaluating asymmetry are needed to fully depict function after knee injury. If we had enrolled participants in this study that did not meet the clinical threshold of >90% LSI in hop distance inclusion criteria, we hypothesize that inter-limb differences in joint power profiles would have been further exacerbated in these individuals. Future work will need to confirm this hypothesis. Importantly, we do not believe our findings undermine the value of the return to sport battery of test. Not passing these criteria has been associated with higher reinjury rates[3] and higher risk of graft rupture.[27] Our results encourage the integration of the best research practices with clinical expertise. We recognize that not all clinical settings will have the infrastructure to implement this data analysis technique. However, as a whole, the sports medicine community would benefit from literature that is grounded in more rigorous data analyses that can better guide clinical practice. We also encourage facilities with the capability, to consider the simultaneous assessment of the timing and magnitude of lower extremity asymmetries that current clinical testing can mask in order to gain a more objective and comprehensive assessment of dynamic movement.[20]

Limitations

These tests were performed in a controlled environment and do not directly translate to practice or game situations. We also did not control for limb dominance due to a smaller sample which may impact results. The subjects we included in this study were of mixed graft types, considered chronic (on average 4 ± 3 yrs removed from surgery), and all passed return to sport testing with a LSI >90% in hop distance. Further work needs to be done on individuals unable to achieve 90% LSIs and to investigate the quality of movement in healthy controls. Additionally, future studies should include these analyses at return to sport to determine the utility of these analyses to expand return to sport assessments. Using diverse analyses in the frontal and transverse planes and increasing our sample size may expand the findings and emphasize the advantages of the functional data analysis compared to discrete analyses. While joint power is a representation of concentric and eccentric muscle activity, including electromyography data can determine muscle activations patterns to help classify movement strategies. It is important to note that clinicians may have limited access to perform these analyses. We encourage researchers with the capability to do so and to collaborate with clinicians to optimize movement assessments.

CONCLUSION

Discrete analyses revealed differences in peak knee power and work, but failed to detect differences at the ankle or hip. Only by performing functional data analyses we were able to uncover the timing and intricacy of lower limb asymmetries that are masked by clinical metrics such as LSI’s and discrete biomechanical analyses. Most notably, we found asymmetries were present at the ankle, knee and hip in the ACLR limb and predominantly stemmed from the inability of the knee to appropriately absorb energy during eccentric landing. Laboratory analyses that comprehensively evaluate movement should be considered to provide patients and clinicians alike with more precise biomechanical asymmetries to target in recovery.

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Table 1. Patient demographics and group comparisons.

	ACLR group (n = 15)	Control group (n = 15)	P
Females/males	6/9	9/6	-
Age (yr)	21 ± 3	23 ± 2	0.355
Height (m)	1.74 ± 0.11	1.68 ± 0.14	0.202
Mass (kg)	72.97 ± 12.28	67.75 ± 13.36	0.968
Time after surgery (yr)	4 ± 3	NA	-
Tegner Activity Scale	Pre: 8 ± 1 Post: 7 ± 1	Pre: 8 ± 2 Post: 8 ± 2	0.597 0.536
Hop Distance (m)	ACLR limb = 4.39 ± 0.7 Contralateral Limb = 4.56± 0.7	Representative Limb = 4.75 ± 0.8 Non-representative Limb = 4.61 ± 0.9	-
Limb Symmetry Index	96 ± 4 %	100 ± 7 %	-

Data are mean ± standard deviation and significance level between groups.

Table 2. Joint power and joint work during the triple hop using traditional discrete analyses.

Joint Power (W·kg^{-1})		ACLR	Contralateral	Control	ACLR vs Contralateral	ACLR vs Control
Eccentric Phase	Ankle	-4.57±0.58	-4.75±0.66	-5.34±0.60	t=0.216 p=0.832	t=0.910 p=0.370
	Knee	-14.11±1.17	-16.93±1.31	-17.21±1.13	t=2.699 p=0.017*	t= 1.899 p=0.068
	Hip	-4.88±0.70	-5.06±0.78	-5.64±0.60	t=0.212 p=0.835	t=0.824 p=0.417
Concentric Phase	Ankle	13.65±1.23	14.84±1.48	14.72±1.48	t=-0.530 p=0.605	t=-0.555 p=0.584
	Knee	4.06±0.44	4.64±0.29	4.83±0.50	t=-1.463 p=0.165	t=-1.151 p=0.260
	Hip	4.32±0.51	3.77±0.34	3.97±0.27	t=1.453 p=0.168	t=0.596 p=0.557
Joint Work (J·kg^{-1})		**ACLR**	**Contralateral**	**Control**	**ACLR vs Contralateral**	**ACLR vs Control**
Eccentric Phase	Ankle	-0.55±0.06	-0.59±0.08	-0.62±0.07	t=-0.306 p=0.764	t=0.766 p=0.450
	Knee	-0.65±0.06	-0.84±0.06	-0.93±0.05	t=-4.066 p=0.001*	t=3.554 p=0.001*
	Hip	0.16±0.03	0.11±0.03	0.08±0.02	t=-1.371 p=0.192	t=1.950 p=0.061
Concentric Phase	Ankle	0.99±0.07	1.10±0.11	1.13±0.08	t=0.642 p=0.531	t=-1.345 p=0.189
	Knee	0.24±0.03	0.30±0.03	0.35±0.03	t=1.682 p=0.115	t=-2.486 p=0.019*
	Hip	0.06±0.03	0.09±0.04	0.10±0.03	t=0.575 p=0.574	t=-0.845 p=0.405

Data are depicted as mean ± standard error. * indicates significance level $p<0.05$.
Joint power during the eccentric phase (initial contact to peak dorsiflexion, knee flexion, and hip flexion) represents energy absorption. Joint power during the concentric phase (peak dorsiflexion, knee flexion, and hip flexion to toe-off) represents energy generation. Joint work during the eccentric phase represents work during energy absorption. Joint work during the concentric phase represents work during energy generation.

Table 3. Percent stance (%) of peak power during the triple hop using traditional discrete analyses.

	ACLR	Contralateral	Control	ACLR vs Contralateral	ACLR vs Control
Eccentric Phase					
Ankle	28.1±2.4	29.1±3.5	22.5±3.7	t=0.398 p=0.697	t=1.253 p=0.222
Knee	15.4±1.0	14.7±1.0	13.3±0.8	t=1.323 p=0.207	t= 1.624 p=0.116
Hip	10.8±0.9	11.0±0.9	9.8±0.7	t=-0.203 p=0.842	t=0.881 p=0.386
Concentric Phase					
Ankle	86.6±1.0	86.7±1.0	88.8±0.9	t=0.106 p=0.917	t=-1.662 p=0.108
Knee	75.5±2.1	75.8±1.9	80.4±1.3	t=-0.225 p=0.825	t=-1.937 p=0.065
Hip	46.0±5.3	54.3±4.5	56.6±4.7	t=-2.090 p=0.055	t=-1.495 p=0.146

Data are depicted as mean ± standard error. * indicates significance level $p<0.05$.
Data represents the percent stance where peak power occurred in the eccentric phase (initial contact to peak dorsiflexion, knee flexion, and hip flexion) and concentric phase (peak dorsiflexion, knee flexion, and hip flexion to toe-off).

Figure Legends

Figure 1) Figure 1- Lower extremity joint powers between the ACLR limb and contralateral limb of the ACLR group during the triple hop. The dashed vertical line was used to distinguish the eccentric and concentric phases of movement. Average power of the ankle (A), knee (C) and hip (E) for both limbs are shown on the left (panels A (ankle), C (Knee) ,E(Hip)) with the shaded regions indicating significant differences between limbs. Results from the functional analysis of variance are shown on the right (panels B (ankle), D (knee), and F (hip)) where the mean difference between limbs is plotted with the 95% confidence intervals shown in grey. A significant ($P<0.05$) difference was found where the confidence intervals did not overlap the zero line. The ACLR knee absorbed as much as 18% (or -1.94 W/kg) less eccentric power than the contralateral knee between 7-16% of stance and the ACLR hip produced as much as 85% (or 1.28 W/kg) more concentric power between 22 and 31% of stance.

Figure 2) Figure 2- Lower extremity joint powers between the ACLR limb and representative control limb during the triple hop. The dashed vertical line was used to distinguish the eccentric and concentric phases of movement. Average power of the ankle (A), knee (C) and hip (E) for both limbs are shown on the left with the shaded regions indicating significant differences between limbs. Results from the functional analysis of variance are shown on the right (panels B (ankle), D (knee), and F (hip)) where the mean difference between limbs is plotted with the 95% confidence intervals shown in grey. A significant ($P<0.05$) difference was found where the confidence intervals did not overlap the zero line. The ACLR ankle absorbed as much as 45% (or -0.88 W/kg) and 29% (or -0.71 W/kg) more eccentric power than the control limb between 13-19% and 45-59% of stance. The ACLR knee absorbed as much as 31% (or -2.24 W/kg) less eccentric power than the control knee between 3-11% and produced as much as 34% (or 0.91 W/kg) less than the control limb during 79-90% of stance. The ACLR knee produced as much as 34% (or 0.86 W/kg) more concentric power than the control limb between 56 and 69%. The ACLR hip produced as much as 78% (or 1.20 W/kg) more concentric power than the control hip between 21-29% and 75% (or 0.86 W/kg) less concentric power during 35-44 % of stance. The ACLR hip absorbed as much as 73% (or -1.04 W/kg) less eccentric power between 92-98% of stance.