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The Utility of Functional Data Analyses to Reveal Between-Limbs Asymmetries in Those With a History of Anterior Cruciate Ligament Reconstruction

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Context: Researchers have traditionally used motion capture to quantify discrete data points (peak values) during hop testing. However, these analyses restrict the evaluation to a single time point (ie, certain percentage of stance) and provide only a narrow view of movement. Applying more comprehensive analyses may help investigators 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 using discrete (ie, single time point) evaluations in participants with a history of anterior cruciate ligament reconstruction (ACLR) who achieved clinical hop symmetry.

Design: Cross-sectional study.

Setting: Laboratory.

Patients or Other Participants: Fifteen participants with unilateral ACLR (age = 21 ± 3 years, time from surgery = 4 ± 3 years) and 15 control participants without ACLR (age = 23 ± 2 years).

Intervention(s): Lower extremity biomechanics during the triple–hop-for-distance task for the ACLR and contralateral limbs of patients and a representative limb of control participants were measured.

Main Outcome Measure(s): Peak sagittal-plane joint power, joint work, and power profiles were determined.

Results: Using discrete analyses, we identified lower peak knee power and work in the ACLR limb compared with the contralateral and control limbs ($P < .05$) but were unable to demonstrate differences at the ankle or hip. Using functional data analyses, we observed asymmetries at the ankle, knee, and hip between the ACLR and contralateral or control limbs throughout stance ($P < .05$), and it was revealed that these asymmetries stemmed from knee power deficits that were prominent during early loading.

Conclusions: Despite achieving hop-distance symmetry, the ACLR knees absorbed less power. Although this information was revealed using discrete analyses, underlying asymmetries at the ankle and hip were masked. Using functional data analyses, we found interlimb asymmetries at the ankle, knee, and hip. Importantly, we found that functional data analyses more fully elucidated the extent and source of asymmetries, which can be used by clinicians and researchers alike to aid in clinical decision making.

Key Words: knee, limb symmetry, kinetics

Key Points

- Clinical (limb symmetry indices) and discrete (peak values) analyses did not capture the full scope of asymmetry.
- Functional data analyses provided more comprehensive evaluations of movement by comparing between-limbs differences in both time and magnitude.
- Current clinical and research assessments can mask underlying movement strategies. Researchers should adapt more in-depth analyses to fully capture asymmetry in order to direct evidence-based practices used in clinical decision making.

To protect athletes against recurrent injury, many clinicians use a battery of tests that primarily rely on limb symmetry indices to assess functional movement before releasing athletes to 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] suggest we need to better understand the factors that contribute to inadequate recovery and develop more comprehensive assessments of dynamic movement. Currently, as part of a battery of tests, many patients are evaluated via a series of functional hop tests[9–11] to determine whether they can hop as far on the ACLR limb as on the contralateral limb. Individuals who achieve at least 90% of the 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 that a between-limbs comparison may not be sufficient to release a patient to return to sport.

Table 1. Patient Characteristics and Group Comparisons

Characteristic	Group: Anterior Cruciate Ligament Reconstruction (n = 15)	Group: Control (n = 15)	*P* Value
Females/Males	6/9	9/6	NA
	Mean ± SD		
Age, y	21 ± 3	23 ± 2	.36
Height, m	1.74 ± 0.11	1.68 ± 0.14	.20
Mass, kg	72.97 ± 12.28	67.75 ± 13.36	.97
Time after surgery, y	4 ± 3	NA	NA
Tegner Activity Scale score			
Pretask	8 ± 1	8 ± 2	.60
Posttask	7 ± 1	8 ± 2	.54
Limb symmetry index, %	96 ± 4	100 ± 7	.09

Abbreviation: NA, not applicable.

Researchers[6,14,15] have proven this theory by using biomechanical methods that often demonstrate kinematics and kinetics at discrete time points (eg, peak values) during hop testing and have repeatedly shown that, despite achieving hop-distance symmetry, ACLR limbs exhibited lower peak knee-flexion angle, peak knee-extension moment, and peak knee power than contralateral or control limbs, or both, during single-hop tasks. Although important, the discrete approach of evaluating only peak values provides the investigator with just a snapshot of how the joint in question is moving at a single time point (ie, percentage of stance) and may overlook other important movement characteristics. In addition, discrete analyses most often evaluate only the knee and do not consider the intricate combination of movement strategies used at the ankle, knee, and hip to complete the task. Simultaneously analyzing movement characteristics during the task (ie, timing and magnitude of interlimb differences) may provide clinicians with further knowledge regarding underlying asymmetries that are masked by discrete analyses and may be barriers to reaching optimal recovery.[5,16]

Of broader significance, evidence-based medicine integrates the best scientific evidence with clinical expertise to guide informed decisions that align with the patient's goals and values. Current clinical and research assessments are incomplete and can mask underlying movement strategies. Therefore, the purpose of our study was to examine the utility of functional data analyses to reveal between-limbs asymmetries that are undetectable by discrete (ie, single time point) evaluations in individuals with a history of ACLR who achieve clinical hop symmetry. We assessed between-limbs differences in joint power and joint work in individuals post-ACLR who achieved clinically acceptable levels of limb symmetry (>90% limb symmetry index [LSI]) on the triple–hop-for-distance (triple-hop) task. To further extend our study, a healthy control group without ACLR was included to reveal inherent asymmetries that are specific to those without a history of knee injury. We anticipated that, compared with the discrete analyses that reveal the magnitude of difference from a snapshot of movement and often only consider the knee, performing functional data analyses of all lower extremity joints would provide a more comprehensive evaluation of movement and detect asymmetries masked by discrete analyses that allow individuals with a history of ACLR to achieve clinical limb symmetry. The application of a functional data analysis to the field is highly relevant, as this type of analysis 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

Participants

Fifteen patients who had undergone primary unilateral ACLR (age = 21 ± 3 years, height = 1.74 ± 0.11 m, mass = 72.97 ± 12.28 kg, time from surgery = 4 ± 3 years) were recruited from the Department of Orthopaedic Surgery at the University of Connecticut and participated in this study. To characterize healthy movement profiles during the triple-hop task, we matched them with 15 healthy individuals who had no history of lower extremity surgery by age, height, mass (age = 23 ± 2 years, height = 1.68 ± 0.14 m, mass = 67.75 ± 13.36 kg), and activity level. Additional patient characteristics can be found in Table 1. All patients with a history of ACLR had completed standard rehabilitation protocols and been cleared by their orthopaedic surgeon to return to unrestricted functional activities. All participants in both groups clinically passed the triple-hop test with at least a 90% LSI, measured as hop-test distance of the ACLR limb/contralateral limb × 100%. Patients were excluded from the study if they had undergone previous knee surgery other than the current ACLR, had sustained a contralateral lower extremity injury within the 6 months before the study, were pregnant, had a cardiac pacemaker, were allergic to adhesives, or had any open skin lesions. All participants provided informed consent, and this level 3 evidence retrospective cohort study was approved by the Institutional Review Board at the University of Connecticut.

Procedures

A 12-camera motion-capture system (Vicon; Oxford Metrics, Yarnton, Oxfordshire, UK) synchronized with 2 force plates (Bertec Corp, Columbus, OH) was used to record kinematic and kinetic data at 240 Hz and 1200 Hz, respectively. After measuring the participants' height and mass, we applied 37 retroreflective markers as previously depicted.[17] The motion-analysis system was calibrated, and a static trial was collected to determine the joint centers of rotation, define the respective joint and segmental coordinate axes, and establish neutral alignment as a reference for subsequent kinematic measures. Participants were instructed to complete the triple-hop task as described by Noyes et al[10] in which bilateral lower extremity sagittal-plane kinetics and kinematics were simultaneously captured. We selected this task because it requires a high level of dynamic control and allows the assessment of a participant's ability to produce, transfer, and absorb force consecutively through 3 hops. The triple-hop task was performed bilaterally, and the order of limb testing was randomized for each person. Participants were allowed 2 practice trials for each limb, and data collection ended when 3 successful trials were collected for each limb. A trial was considered *successful* if the full foot landed on the force plate on the second of 3 hops and if the participant was able to maintain balance on only the take-off limb for at least 1 second during the landing of the last hop. Given that only the second hop provided force-plate data, these trials were used in subsequent analyses. At most, 5 trials were required to attain 3 successful trials for each limb. Marker trajectories were exported to Visual3D software (C-Motion Inc, Germantown, MD) for processing. Kinematic and ground reaction force data were filtered using a fourth order, zero-lag, low-pass Butterworth filter with a cut-off frequency of 12 Hz.[18] A kinematic model that consisted of 8 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 the Visual3D X-Y-Z convention (flexion or extension, abduction or adduction, and internal or 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 independent analysis of the ankle, knee, and hip joints during each phase.[19] Joint moments were determined using a standard inverse-dynamics approach and were normalized to body mass. Joint power was calculated as the product of joint moment and angular velocity and was evaluated because it reflects the energy generation, transfer, and absorption that the triple-hop task demands. Positive joint power represented the concentric phase of energy generation, and negative joint power represented 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. Given that the data were normalized to 100% of stance to allow for group comparisons, timing was considered to be relative. In the ACLR group, both the ACLR and contralateral limbs were analyzed. In the control group, a representative limb, matched to the ACLR limb, was analyzed. For instance, 53% (8/15) of the ACLR group underwent surgery on their right limb, so we assessed the right limb in 53% (8/15) of the control group[20,21] using random assignment.

Statistical Analysis

Independent *t* tests were performed to evaluate if there were differences in the descriptive variables between the ACLR and control groups. For the discrete analyses, the global average of 3 successful trials was used in the analysis. Paired (ACLR and contralateral limbs) and independent (ACLR and control limbs) *t* tests were calculated to assess between-limbs differences in peak joint power and joint work and the percentage of stance when peak power occurred in the eccentric and concentric phases of movement. To extend the aforementioned discrete analyses and detect differences in joint power across all of stance, we computed functional analyses of variance (FANOVAs) using the functional data analysis package in RStudio (version 1.1.456; Boston, MA) to compare the ACLR and contralateral limbs and the ACLR and control limbs. A benefit of the FANOVA is that it evaluates between-groups variances by identifying systematic differences among all trials of a group. This method enabled us to include 3 trials per participant rather than only a global average.[22] Between-limbs comparisons at each percentage of stance with the corresponding 95% CIs were plotted alongside ensemble group averages. Results of the interlimb comparisons were considered different when the 95% CIs did not overlap zero, indicating a *P* value of $<$.05. All data analyses were performed using RStudio, and the α level was set at .05.

RESULTS

No differences in descriptive data were found between groups (Table 1). As noted, 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 described earlier.[19] For the ACLR, contralateral, and control limbs, peak dorsiflexion, knee flexion, and hip flexion occurred at 63% $\pm$ 8%, 50% $\pm$ 6%, and 24% $\pm$ 8% of stance, respectively.

Discrete Analyses

Using only discrete values, we observed that the peak knee power of the ACLR limb was lower than that of the contralateral limb during the eccentric phase ($t_{14} = 2.699$, $P = .02$; Table 2). The ACLR knee performed less work than the contralateral knee during the eccentric phase ($t_{14} = -4.066$, $P = .001$) and the control knee during the eccentric ($t_{28} = 3.554$, $P = .001$) and concentric ($t_{28} = -2.486$, $P = .02$) phases. Notably, the discrete approach did not identify any differences in joint power or work at the ankle or hip. This approach also did not reveal any differences in the percentage of stance at which peak power occurred (ie, no differences in the time of peak power were present 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) of the ACLR knee between 7% and 16% of stance (Figure 1D; $P < .05$). This was followed by an increase in concentric power of the ACLR hip between 22% and 31% of stance (Figure 1F; $P < .05$).

Figure 2 provides the results of the FANOVA between the ACLR and control limbs for joint power. Asymmetries between limbs were found at the ankle, knee, and hip. Similar to the ACLR versus contralateral limb, asymmetries between the ACLR and control limbs were initiated by a decrease in eccentric power (energy absorption) of the ACLR knee between 3% and 11% of stance (Figure 2D; $P < .05$). This was immediately followed by a minimal but significant increase in power of the ACLR ankle and ACLR hip between 13% and 19% and between 21% and 29% of stance, respectively (Figure 2B and F; $P < .05$). Differences at the ankle, knee, and hip persisted throughout the rest of stance, most prominently at the hip between 35% and 44% and between 92% and 98% and at the knee between 56% and 69% and between 79% and 90% of stance (Figure 2; $P < .05$).

Table 2. Joint Power and Joint Work During the Triple–Hop-for-Distance Task Using Traditional Discrete Analyses

Parameter	Limb, Mean ± SE: Anterior Cruciate Ligament Reconstruction	Limb, Mean ± SE: Contralateral	Limb, Mean ± SE: Control	Anterior Cruciate Ligament Reconstruction Versus Contralateral Limb: t_{14} Value	Anterior Cruciate Ligament Reconstruction Versus Contralateral Limb: *P* Value	Anterior Cruciate Ligament Reconstruction Versus Control Limb: t_{28} Value	Anterior Cruciate Ligament Reconstruction Versus Control Limb: *P* Value
Joint power, W/kg							
Eccentric phase[a]							
Ankle	−4.57 ± 0.58	−4.75 ± 0.66	−5.34 ± 0.60	0.216	.83	0.910	.37
Knee	−14.11 ± 1.17	−16.93 ± 1.31	−17.21 ± 1.13	2.699	.02[a]	1.899	.07
Hip	−4.88 ± 0.70	−5.06 ± 0.78	−5.64 ± 0.60	0.212	.84	0.824	.42
Concentric phase							
Ankle	13.65 ± 1.23	14.84 ± 1.48	14.72 ± 1.48	−0.530	.61	−0.555	.58
Knee	4.06 ± 0.44	4.64 ± 0.29	4.83 ± 0.50	−1.463	.17	−1.151	.26
Hip	4.32 ± 0.51	3.77 ± 0.34	3.97 ± 0.27	1.453	.17	0.596	.56
Joint work, J/kg							
Eccentric phase							
Ankle	−0.55 ± 0.06	−0.59 ± 0.08	−0.62 ± 0.07	−0.306	.76	0.766	.45
Knee	−0.65 ± 0.06	−0.84 ± 0.06	−0.93 ± 0.05	−4.066	.001[a]	3.554	.001[a]
Hip	0.16 ± 0.03	0.11 ± 0.03	0.08 ± 0.02	−1.371	.19	1.950	.06
Concentric phase							
Ankle	0.99 ± 0.07	1.10 ± 0.11	1.13 ± 0.08	0.642	.53	−1.345	.19
Knee	0.24 ± 0.03	0.30 ± 0.03	0.35 ± 0.03	1.682	.12	−2.486	.02[a]
Hip	0.06 ± 0.03	0.09 ± 0.04	0.10 ± 0.03	0.575	.57	−0.845	.41

[a] Indicates difference ($P < .05$).

DISCUSSION

We examined the utility of functional data analyses to reveal between-limbs asymmetries that were masked by discrete analyses in a cohort with ACLR and a cohort with healthy limbs (ie, no ACLR) that achieved clinically acceptable levels of hop symmetry for the triple-hop task. Our purpose was to use more comprehensive analyses to reveal characteristics (eg, timing and magnitude) of the task that the current oversimplified analyses do not consider but may be better indicators of function and the quality of movement than LSIs and discrete analyses. Of broader importance, in this proof-of-concept study, we showed that a functional data analysis can be adopted by sports medicine researchers to provide clinicians with critical insight into interlimb asymmetries that are not captured by current clinical and research assessments. These asymmetries may contribute to suboptimal outcomes, and thus, this evaluation strategy can be used to refine rehabilitation protocols.

In line with work by previous researchers,[5,15] our discrete and functional data analyses revealed a decrease in peak knee power of the ACLR limb during eccentric landing that was not captured in clinical analyses (<90% LSI). To this point, others[23] have suggested that clinical metrics, such as LSIs, overestimate function by not identifying underlying biomechanical alterations and movement strategies during single-limb hop tasks. Our findings provided direct evidence for this, further confirming that passing the 90% LSI criterion for hop distance does not equate to symmetry in biomechanical outcomes.

The only asymmetries detected using the discrete analyses were reduced knee power and work (Table 2). The functional data analyses were able to extend this key insight by determining the magnitude of interlimb asymmetries and the timing of stance when the significant

Table 3. Percentage of Stance at Peak Power During the Triple–Hop-for-Distance Task Using Traditional Discrete Analyses[a]

Phase	Limb, Mean ± SE: Anterior Cruciate Ligament Reconstruction	Limb, Mean ± SE: Contralateral	Limb, Mean ± SE: Control	Anterior Cruciate Ligament Reconstruction versus Contralateral Limb: t_{14} Value	Anterior Cruciate Ligament Reconstruction versus Contralateral Limb: *P* Value	Anterior Cruciate Ligament Reconstruction versus Control Limb: t_{28} Value	Anterior Cruciate Ligament Reconstruction versus Control Limb: *P* Value
Eccentric							
Ankle	28.1 ± 2.4	29.1 ± 3.5	22.5 ± 3.7	−0.398	.70	−1.253	.22
Knee	15.4 ± 1.0	14.7 ± 1.0	13.3 ± 0.8	1.323	.21	−1.624	.12
Hip	10.8 ± 0.9	11.0 ± 0.9	9.8 ± 0.7	−0.203	.84	−0.881	.39
Concentric							
Ankle	86.6 ± 1.0	86.7 ± 1.0	88.8 ± 0.9	−0.106	.92	1.662	.11
Knee	75.5 ± 2.1	75.8 ± 1.9	80.4 ± 1.3	−0.225	.83	1.937	.07
Hip	46.0 ± 5.3	54.3 ± 4.5	56.6 ± 4.7	−2.090	.06	1.495	.15

[a] Data represent the percentage of stance in which 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).

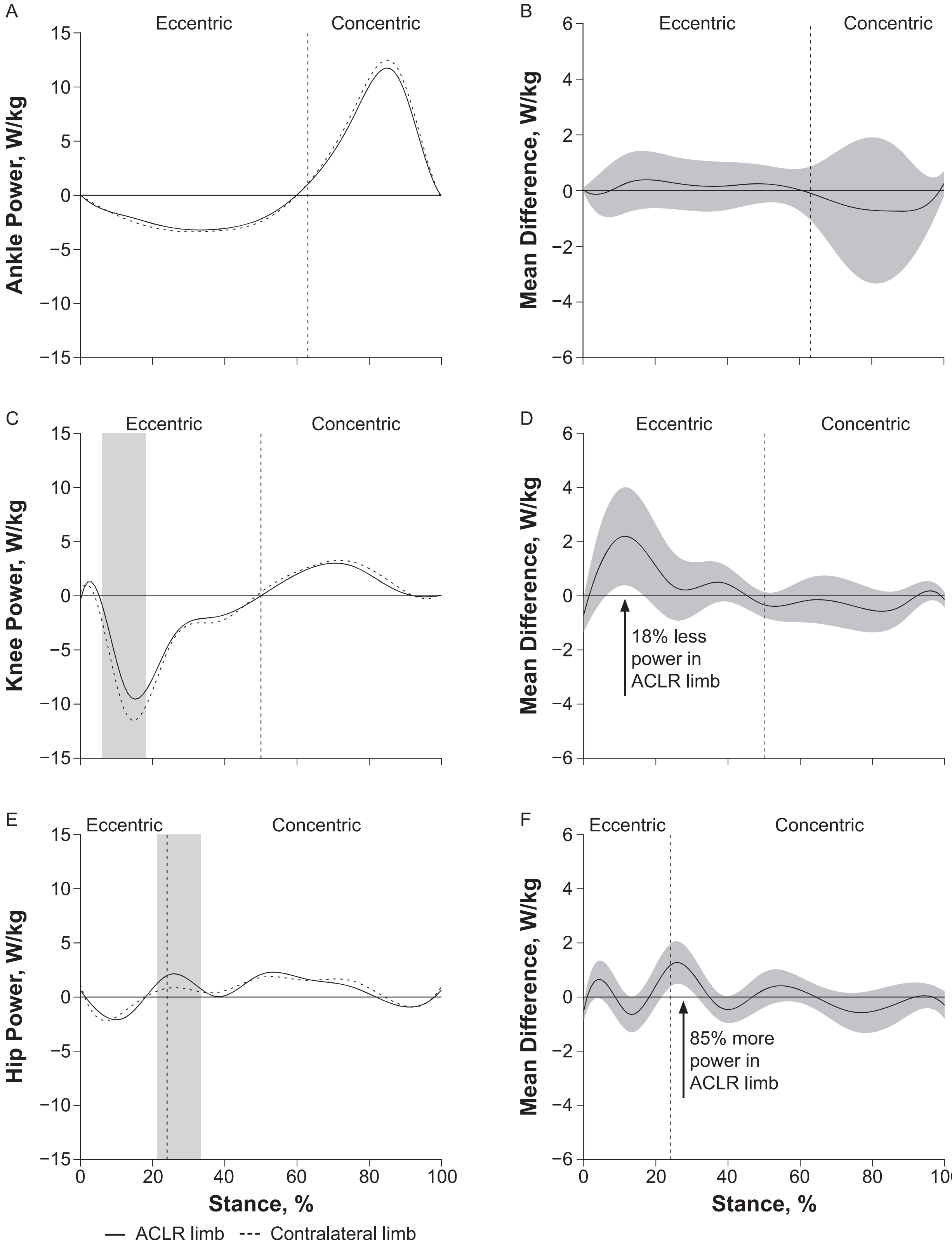

Figure 1. Lower extremity joint power in the anterior cruciate ligament reconstruction (ACLR) limb and contralateral limb of the ACLR group during the triple–hop-for-distance task. The dashed vertical line distinguishes the eccentric and concentric phases of movement. A, average ankle power. B, functional analysis of variance (FANOVA) of the ankle. C, average knee power. D, FANOVA of the knee. E, average hip power; F, FANOVA of the hip. A, C, and E, shaded regions indicate differences between limbs ($P < .05$). B, D, and F, the mean difference between limbs is plotted, with the 95% CIs shown in grey. Differences were observed when the 95% CIs did not cross zero ($P < .05$). The ACLR knee absorbed as much as 18% (or −1.94 W/kg) less eccentric power than that of the contralateral knee between 7% and 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.

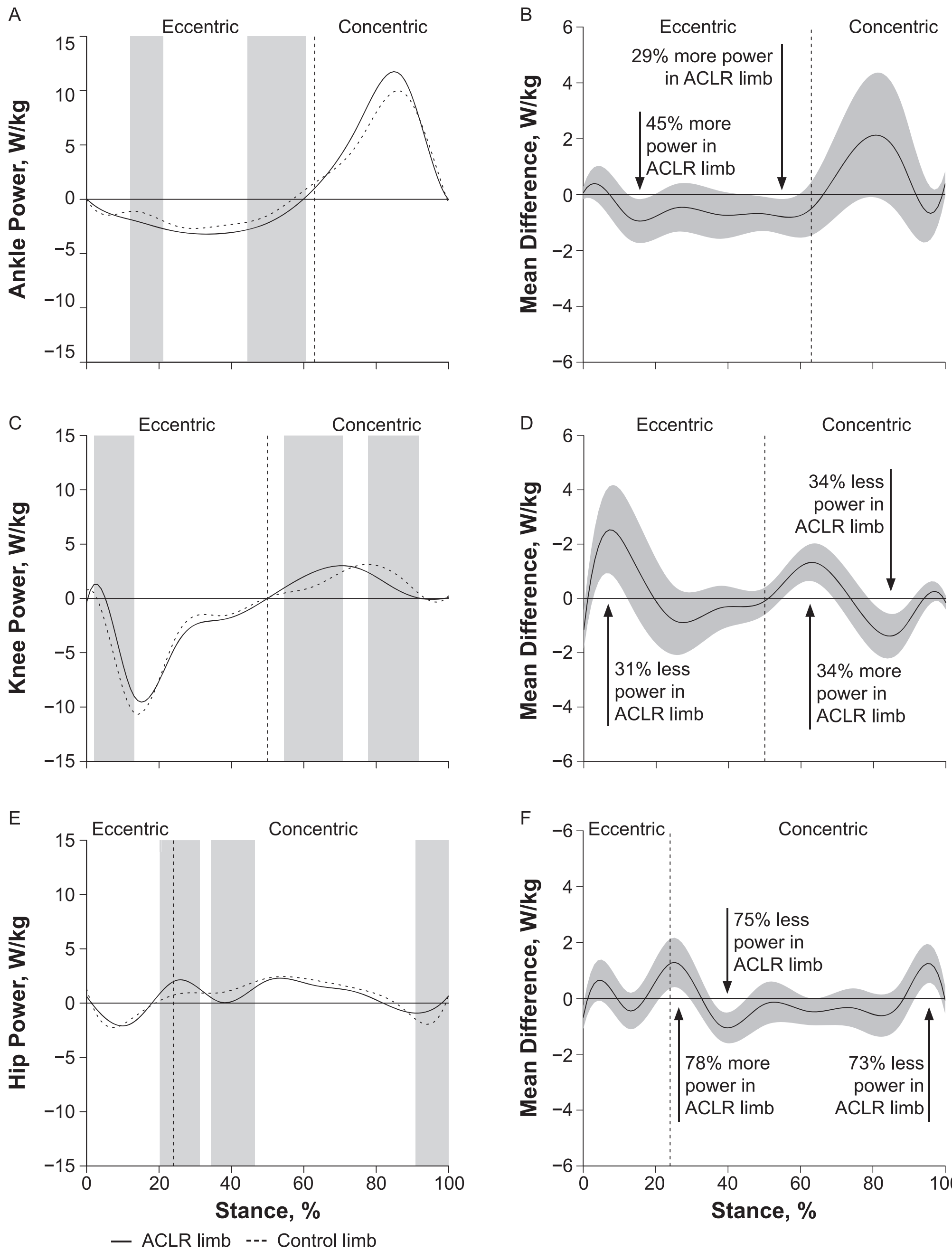

Figure 2. Lower extremity joint power in the anterior cruciate ligament reconstruction (ACLR) limb and representative control limb during the triple–hop-for-distance task. The dashed vertical line distinguishes the eccentric and concentric phases of movement. A, average ankle power; B, functional analysis of variance (FANOVA) of the ankle. C, average knee power; D, FANOVA of the knee. E, average hip power; F, FANOVA of the hip. A, C, and E, shaded regions indicate differences between limbs ($P < .05$). B, D, and F, the mean difference between limbs is plotted, with the 95% CIs shown in grey. Differences were observed when the 95% CIs did not cross zero ($P < .05$). The ACLR ankle absorbed as much as 45% (–0.88 W/kg) and 29% (–0.71 W/kg) more eccentric power than the control limb between 13% and 19% and 45% and 59% of stance. The ACLR knee absorbed as much as 31% (–2.24 W/kg) less eccentric power than the control knee between 3% and 11% of stance and produced as much as 34% (0.91 W/kg) less concentric power than the control limb during 79% to 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% of stance. The ACLR hip produced as much as 78% (or 1.20 W/kg) more concentric power than the control hip between 21% and 29% of stance and 75% (or 0.86 W/kg) less concentric power during 35% to 44% of stance. The ACLR hip absorbed as much as 73% (or –1.04 W/kg) less eccentric power between 92% and 98% of stance.

interlimb asymmetries occurred. This approach uniquely identified asymmetries between all lower extremity joints and, from the timing information, revealed that there were sequential joint compensations in the ACLR cohort that stemmed from decreased energy absorption (ie, decrease in power) by the ACLR knee in early loading. This is clinically important, as adequate energy absorption permits the dissipation of forces through eccentric muscle action. Without adequate energy absorption, energy and mechanical work are redistributed, which leads to abnormal loads at the knee. Given the previously established connection between abnormal joint loading and joint disease progression[24,25] and injury risk,[19] our finding of reduced joint power in the ACLR limb during early loading is highly important. As a natural extension of this result, we recommend that clinicians consider the concentrated use of eccentric exercise in rehabilitation to mitigate this early landing asymmetry.[17] Future research should combine this rehabilitation approach with more comprehensive assessments of interlimb asymmetries during dynamic tasks to test this hypothesis. Moreover, as a field we need to establish the clinical meaningfulness of interlimb asymmetries in order to better understand how asymmetries contribute to injury risk.

We suggest that more robust techniques for evaluating asymmetry are needed to fully characterize function after knee injury. If we had enrolled participants who did not meet the inclusion criterion of >90% LSI in hop distance, we hypothesize that interlimb differences in joint power profiles would have been further exacerbated. Importantly, we do not believe our findings undermine the value of the return-to-sport battery of tests. Not passing these criteria has been associated with higher reinjury rates[3] and a higher risk of graft rupture.[26] We encourage the integration of rigorous research practices with the best clinical expertise. We recognize that not all clinical settings will have the infrastructure to implement this data-analysis technique. Still, 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 clinicians in facilities with the capability of performing advanced analyses (ie, timing and magnitude of interlimb asymmetries) to do so to gain a more objective and comprehensive assessment of dynamic movement that can be masked in current clinical testing.[19]

Our study had 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 because of the small sample size, which may have affected the results. The ACLR group had mixed graft types, was considered to have long-standing ACLR (time after surgery = 4 ± 3 years), and had passed return-to-sport testing with an LSI >90% in hop distance. Researchers should conduct additional examinations of individuals unable to achieve 90% LSIs to investigate the quality of movement in those without a history of ACLR or pathologic knee conditions. In future studies, researchers should also include these analyses at return to sport to determine their utility for expanding return-to-sport assessments. The use of diverse analyses in the frontal and transverse planes and increasing the sample size may enhance these findings and emphasize the advantages of functional data analyses compared with discrete analyses. Whereas the joint power measurement represents concentric and eccentric muscle activity, including electromyography, the data can be used to determine muscle-activation patterns and help classify movement strategies. However, clinicians may have limited ability to perform these analyses. We encourage investigators who can perform these analyses to collaborate with clinicians to optimize movement assessments.

CONCLUSIONS

Using discrete analyses, we revealed differences in peak knee power and work but did not detect differences at the ankle or hip. Only by performing functional data analyses were we able to determine the timing and intricacy of lower limb asymmetries that were masked by clinical metrics, such as LSIs and discrete biomechanical analyses. Most notably, we found asymmetries at the ankle, knee, and hip in the ACLR limb that predominantly stemmed from the inability of the knee to appropriately absorb energy during eccentric landing. Laboratory analyses that comprehensively evaluate movement should be considered so that patients and clinicians can more precisely target biomechanical asymmetries during recovery after ACLR.

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