# Comparison of Joint Moments and Joint Contributions to Total Support Moment during the Propulsive Phase of a Triple Hop Task between Healthy and ACL Reconstructed Females

by
Emma Gibbs

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Kinesiology
(Honors Associate)

Presented May 28, 2020
Commencement June 2020

# AN ABSTRACT OF THE THESIS OF

Emma Gibbs for the degree of Honors Baccalaureate of Science in Kinesiology presented on May 28, 2020. Title: Comparison of Joint Moments and Joint Contributions to Total Support Moment during the Propulsive Phase of a Triple Hop Task between Healthy and ACL Reconstructed Females.

Abstract approved: ______________________________________________________
Marc F. Norcross

Recent research suggests that individuals might use compensatory movement patterns in their ACL-reconstructed (ACLR) limb when performing a triple hop (TH) to overcome quadriceps weakness. The purpose of this study was to determine if ACLR females exhibit differences in TH performance compared to previously uninjured females. Nineteen females with ACLR and 19 without completed three THs during which hop distance was recorded and lower extremity biomechanics assessed. Hip, knee, and ankle joint extensor moment impulses, total support moment impulse (TSM), and joint contributions to TSM during the propulsive phase of the first hop were calculated and the influences of previous ACL injury, joint, and their interaction on the outcome variables was assessed. Previous history of ACLR did not influence hop performance, TSM, or individual joint impulse magnitudes or contributions to TSM. However, irrespective of group, the ankle, rather than the knee, produced the greatest joint moment impulse and was the largest contributor to TSM. This suggests that the previously reported lack of association between quadriceps function and single leg TH performance is not the result of compensatory strategies following ACLR, but most likely results from the ankle and not the knee being the primary contributor to propulsion.

Key Words: ACL Reconstruction, Hopping Tasks, Return to Sport, Quadriceps Strength, Compensations
Corresponding e-mail address: gibbse@oregonstate.edu

Comparison of Joint Moments and Joint Contributions to Total Support Moment during the Propulsive Phase of a Triple Hop Task between Healthy and ACL Reconstructed Females

by
Emma Gibbs

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Kinesiology
(Honors Associate)

Presented May 28, 2020
Commencement June 2020

Honors Baccalaureate of Science in Kinesiology project of Emma Gibbs presented on May 28, 2020.
APPROVED:

______________________________
Marc F. Norcross, Mentor, representing Kinesiology

______________________________
Samuel T. Johnson, Committee Member, representing Kinesiology

______________________________
Colin M.S. Mulligan, Committee Member, representing Kinesiology

______________________________
Toni Doolen, Dean, Oregon State University Honors College

I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

______________________________
Emma Gibbs, Author

# CONTRIBUTION OF AUTHORS

Dr. Norcross contributed to conception and design of the work; analysis and interpretation of data, drafting the work or revising it critically for important intellectual content; and final approval of the work. Dr. Johnson contributed to conception and design of the work; revising it critically for important intellectual content; and final approval of the work. Mr. Mulligan contributed to conception and design of the work; the acquisition, analysis, and interpretation of data, revising the work critically for important intellectual content; and final approval of the work.

**INTRODUCTION:**

Anterior cruciate ligament (ACL) ruptures are devastating knee injuries, yet relatively common with an estimated 350,000 occurring each year in the United States (Davies, McCarty, Provencher, & Manske, 2017). One of the biggest issues with ACL ruptures is the high rate of re-injury following reconstructive surgery and rehabilitation. Within five years post-reconstruction, around 11.8% of individuals suffer an ACL injury to the contralateral leg and around 5.8% re-injure the reconstructed ACL. If the individual is young and active, the rate of a second ACL injury can be as high as 30-49% (Barfod, Feller, Hartwig, Devitt, & Webster, 2019; Wellsandt, Failla, & Snyder-Mackler, 2017).

ACL injuries are especially common in female athletes. Before any initial injury, female high school athletes are 1.6 times more likely to tear their ACL than male high school athletes per athletic exposure (Gornitzky, Lott, Yellin, Fabricant, & Ganley, 2017). In a study by Paterno and colleagues, it was determined that female athletes who have had an ACL reconstruction (ACLR) were 5 times more likely to tear their ACL than healthy females, and ACLR females were twice as likely to tear the ACL on their contralateral knee compared to re-injuring their ACLR knee (Paterno, Rauh, Schmitt, Ford, & Hewett, 2014). With such high rates of second ruptures, it is evident our current methods of assessing if an individual is ready to return to play may not be effective for identifying individuals at high risk of re-injury.

Return to play (RTP) tests are commonly used in clinical practice to assess a patient's level of function. Current RTP tests following ACLR generally assess performance by measuring the distance traveled during functional activities like single leg hopping (Thomeé et al., 2011). However, a large facet of RTP criteria focuses on achieving a requisite amount of symmetry between the healthy and ACLR leg of the same individual, rather than using the actual hop distance to guide the RTP decision (Davies, McCarty, Provencher, & Manske, 2017). By simply comparing the performance of the ACLR limb against the uninvolved side, it is possible that an individual's readiness to participate in activities could be overestimated (Wellsandt, Failla, & Snyder-Mackler, 2017). The non-injured leg might suffer deficits following the surgery or may not have been sufficiently strong in the first place. Leister et al. stated that an individual "…may demonstrate good limb symmetry and yet may not be ready for a return to demanding sports because both extremities are less trained than an average healthy individual's" (Leister et al., 2019). Therefore, assessing limb symmetry rather than actual RTP test performance (*i.e.*, distance) could provide false information about a patient's true recovery status.

A second challenge with the use of functional hop tests is that they are commonly used to infer quadriceps strength. Quad strength has been shown to predict ACL functionality but often is not directly measured in a clinical setting (Grindem et al., 2016; Herrington et al., 2018). Many studies researching ACL injury use testing equipment such as an isokinetic dynamometer to measure quadriceps strength in isolation, but this is not always an accessible or feasible method outside of research facilities. In the absence of this equipment, hop tasks are implemented to measure the symmetry between limbs and assess quadriceps functionality (Thomeé et al., 2011). These assessments are often measured by comparing the reconstructed limb against the healthy limb, as well as evaluating the overall quality of the movement. If a patient can obtain between 80%-90% symmetry between limbs in the hop tasks, it is assumed that the strength of the quadriceps are equally symmetrical. This becomes problematic, as multiple studies have reported that there is very little relationship between limb symmetry during a hop test and quadriceps strength (Palmieri-Smith & Lepley, 2015; Barfod, Feller, Hartwig, Devitt, & Webster, 2019; Herbst et al., 2015; Leister et al., 2019; Wellsandt, Failla, & Snyder-Mackler, 2017).

Barfod et al. reported that while only 46.4% of participants had restored quadriceps strength on the ACLR limb to within 85% of their uninvolved limb one year post-surgery, 89.9% of those same participants were classified as having adequate between-limb symmetry during a single hop for distance test (Barfod, Feller, Hartwig, Devitt, & Webster, 2019). Even though the strength of the quadriceps on the ACLR limb was still significantly lower than the non-injured leg, many of these participants were still able to jump close to the same distance on both limbs. It was suggested that in order for these patients to exhibit symmetry in hop distance between limbs without symmetrical quadriceps strength, they might be using an alternate movement strategy to compensate for decreased quadriceps strength which allowed them to achieve the same hop distance (Barfod et al., 2019; Baumgart et al., 2017; Paterno et al., 2014; Ernst, 2000). However, this idea is based on the notion that single leg hop distance is highly related to quadriceps strength and that individuals increase the contributions from the hip and/or ankle on the ACLR limb to compensate for diminished quadriceps strength. To our knowledge, this has not been directly evaluated.

Therefore, the purpose of this study was to determine if ACLR and healthy females: 1) exhibit differences in hop performance and quadriceps strength, and 2) utilize different joint contributions to generate propulsion during a triple hop for distance. We hypothesized that ACLR females would average lower quadriceps strength and would display different joint contributions to total propulsive movement while still performing similarly on hop distance when compared to healthy females.

## METHODS

### *Participants*

A total of 38 female participants (19 ACLR and 19 healthy) between the ages of 16 and 30 volunteered to participate in this investigation. The study protocol was approved by the University's Institutional Review Board. At the beginning of the testing session, informed written consent/assent was obtained from study participants and their legal guardians if participants were under age 18. After study enrollment, participants completed: 1) a general screening questionnaire; 2) the 2000 International Knee Documentation Subjective Knee Evaluation Form (IKDC 2000); 3) the Knee Outcome Survey Activities of Daily Living Scale (KOS-ADLS); and 4) the Tegner activity scale. These questionnaires were used to verify that participants met the study's eligibility criteria.

Females who did not have a history of low back, hip, knee, or ankle surgery except for ACLR and up to one subsequent minor operation for hardware removal, debridement and/or arthroscopic assessment following the primary ACLR participated in this study. All ACLR participants had undergone unilateral primary ACLR surgery and been cleared for unrestricted activities by the orthopedic surgeon who performed the ACLR within the past two years. If an additional subsequent operation following the primary ACLR had been performed, the participant must have reported being cleared for unrestricted activities by the orthopedic surgeon who performed the subsequent operation. This follow-up period was selected because the rates of a second ACL injury 12 and 24 months after return to play in ACLR patients are 15 times (Paterno et al., 2012) and 6 times (Paterno et al., 2014) greater than healthy individuals, respectively.

All participants were recreationally active which was operationally defined as self-reporting participation in moderate to vigorous physical activity (64 - 95% of maximum heart rate) at least 150 minutes per week (Garber et al., 2011). Individuals with: 1) a history of surgery or injury to their back or lower extremity within the past 6 months that limited their physical activity, 2) a neurological or cardiopulmonary disorder, or 3) history of multiple ACLR or graft failure were excluded from this study. Any individuals that scored: 1) less than 2 on question number seven of the IKDC 2000; 2) less than 3 on any item in question number nine of the IKDC 2000; or 3) less than 4 on any question on the KOS-ADLS were also excluded from further participation.

After verifying study eligibility, the height and weight of participants were measured and leg dominance was determined by identifying the leg that was used to complete at least two of following three tasks: kicking a ball for distance, stepping up onto a small step, and recovering from a small perturbation from behind (Hoffman, Schrader, Applegate, & Koceja, 1998). Participants were then instructed to perform a warm-up on a stationary bicycle for five minutes at submaximal intensity.

*Quadriceps strength assessment:*

Quadriceps strength of the ACLR limb of ACLR participants and non-dominant limb of healthy participants was measured as described previously by Huang (2019). Participants were positioned on a Biodex System 3 dynamometer (Biodex Medical Systems, Inc., Shirley, NY) in a sitting position with the trunk reclined to 70° from the horizontal and the testing knee flexed to 70°. The lateral femoral condyle of the testing thigh was aligned to the axis of rotation of the dynamometer and the distal shank of the tested limb was strapped on the dynamometer arm. Shoulder, waist, and thigh straps were also used to secure each participant (Figure 1).

**Figure 1. Participant demonstrating a voluntary isometric muscle contraction in the Biodex**

Participants were instructed to perform quadriceps voluntary isometric muscle contractions at 25%, 50% and 75% of their self-perceived maximal effort for one repetition for each intensity (Pietrosimone et al., 2014). After the warm-up and familiarization, participants were instructed to place their arms across the chest and extend their knee against the dynamometer by performing isometric contraction of the quadriceps muscle "as hard and fast as possible" with a 60-second rest between each trial. A successful trial was identified when no excessive body movement (i.e., engaging hip flexion or trunk extension) was observed no initial countermovement was found when evaluating the torque-time curve immediately after each trial.

*Triple hop assessment*

A standard retro-reflective cluster set was attached to participants (Figure 2) so that kinematic data could be collected using an 8-camera motion-capture system (Optitrack Prime 13, NaturalPoint Inc, Corvallis, OR).

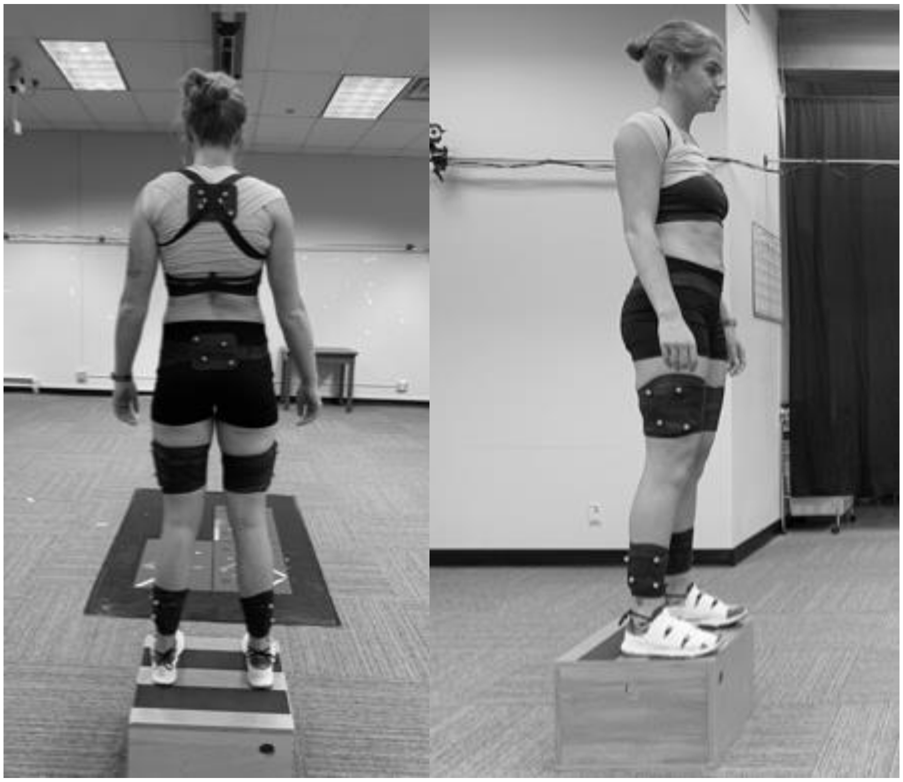


**Figure 2. Placement of cluster sets on participant**

Marker data was streamed using a real-time plug-in to The MotionMonitor software (Innovative Sports Training Inc., Chicago, IL), time-synchronized with data from two force platforms (Bertec Corp., Columbus, OH), and sampled directly using The MonitonMontior software. Once all of cluster sets had been attached, a biomechanical model was generated within The MotionMonitor software by combining segment position data obtained using the clusters with virtual joint center markers created using a standardized digitization protocol. The 3-D coordinates of the hip joint center were estimated based on digitization of the anterior superior iliac supine using the method described by Bell et al. (A. L. Bell, Pedersen, & Brand, 1990). The ankle and knee joint centers were determined as the middle points between the digitized medial and lateral malleolus, and between the digitized medial and lateral epicondyle, respectively. Local coordinate systems for the shank, thigh and pelvis were defined with the positive x-axis directed anteriorly, positive y-axis directed to the left, and the positive z-axis directed superiorly. Cluster positions and force platform data were recorded at 150 and 1,500 Hz, respectively.

Participants were instructed to perform a single-leg triple hop task by hopping three consecutive times in a straight line for maximal distance. Participants began at the start line positioned in the center of the force plate, performed the task, and the location of their heel after landing from the first hop and sticking the final hop were marked. The distances between these marks and the start line were measured in centimeters and recorded, giving us an initial hop distance and a total hop distance (Figure 3).

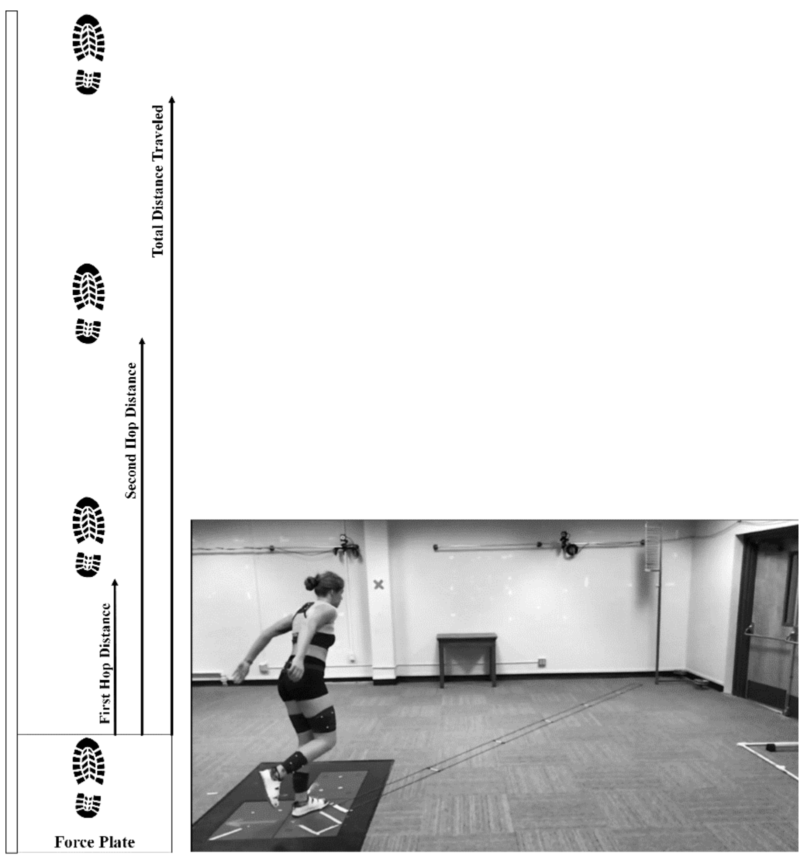



**Figure 3. Triple hop task**

Trials were deemed successful if the participant was able to complete the three hops without the other limb making contact with the ground and was able to “stick” the landing of the final hop and hold for two seconds. Participants were given at least 1 practice trial before completing three successful hop trials with at least 60 seconds of rest between trials.

*Data sampling, processing, and reduction*

The raw voltage signal from the Biodex System 3 dynamometer was sampled at 2000 Hz and stored on a personal computer equipped with a Biopac MP100 data collection system (Biopac Systems Inc., Goleta, CA). Custom computer software (LabVIEW, National Instruments, Austin, TX) was utilized to identify the maximum torque during each of the quadriceps strength trials. Maximum values were normalized by body mass (x kg-1) (Chang, Norcross, Johnson, Kitagawa, & Hoffman, 2015) and averaged across the three trials prior to statistical analysis.

Kinematic and force platform data were filtered using a fourth-order low-pass Butterworth filter with a cutoff frequency of 12 Hz (Bisseling & Hof, 2006). Joint angles were determined as Euler angles based on the distal reference frame relative to the proximal reference frame rotated in an order of flexion-extension (y-axis), valgus-varus (x-axis), and internal-external rotation (z-axis). Net internal hip, knee, and ankle moments were calculated using an inverse dynamics approach described by Gagnon and Gagnon (Gagnon & Gagnon, 1992) within the MotionMonitor software using filtered kinematic, kinetic, and anthropometric data.

A custom computer software program (LabVIEW, National Instruments, Austin, TX) was used to calculate the net hip, knee, and ankle extensor/plantar flexor moment impulses by integrating the area under each respective joint moment-time curve during the propulsive phase of the first hop of the task. The propulsive phase was defined as the time from peak knee flexion to toe-off, which was operationally defined as the instant that the vertical ground reaction force was <10 N. Total support moment impulse was calculated by summing the calculated net extensor/plantar flexor moment (TSM) impulses across joints. Joint contributions to total support moment impulse were expressed as a percentage. All impulse values were normalized to the product of body weight and height (x $[N \cdot m]^{-1}$) and outcome variables averaged across the three hop trials prior to statistical analysis.

*Statistical analysis*

Independent samples *t*-tests were used to assess group differences in participant characteristics, quadriceps strength, hop distances, and TSM. Separate 2 (Group: ACLR and Healthy) x 3 (Joint: Hip, Knee, and Ankle) mixed-model ANOVA models were used to assess the potential influences of prior ACLR, lower extremity joint, and their interaction on the magnitude of net moment impulse and joint contributions to TSM. Planned pairwise comparisons following significant ANOVA models were made using a Bonferroni correction. Statistical significance was set a priori at $\alpha \leq 0.05$.

**RESULTS**

Table 1 summarizes relevant participant characteristics for ACLR and healthy participants. Healthy females exhibited significantly higher average IKDC and KOOS scores and there was a trend for healthy participants to be slightly older than ACLR participants. However, no group differences in height, mass, or Tegner activity score were identified.

**Table 1. Means and SD Participant Characteristics**

| Criterion Variable | ACLR | Healthy | p-value |
|---|---|---|---|
| Age (years) | 19.21 ± 1.81 | 21.12 ± 3.28 | 0.052 |
| Height (m) | 1.63 ± 0.07 | 1.67 ± 0.07 | 0.169 |
| Mass (kg) | 63.08 ± 7.14 | 67.28 ± 9.25 | 0.157 |
| Tegner Activity Score | 6.61 ± 1.75 | 6.52 ± 1.17 | 0.912 |
| IKDC | 89.55 ± 6.60 | 97.76 ± 5.02 | <0.001* |
| KOOS (%) | 95.71 ± 3.83 | 99.55 ± 1.17 | 0.001* |

*Significant difference between groups ($\alpha \leq 0.05$).

The primary findings reveal that there was no difference in initial ($p = 0.721$) or overall triple hop performance ($p = 0.765$) and no difference in TSM impulse during the propulsive phase of the initial hop ($p = 0.506$) between the healthy and ACLR groups (Table 2). Hop symmetry for the ACLR and healthy groups were 96.21% and 98.82%, respectively, with no significant differences in hop symmetry between groups identified ($p = 0.189$). Though ACLR participants exhibited average quadriceps strength that was about 12% less than healthy participants, no significant difference in maximal voluntary isometric contraction (MVIC) of the quadriceps was identified between groups ($p = 0.277$).

**Table 2. Means ± Standard Deviations for Outcome Variables of Interest**

| Criterion Variable | ACLR Limb | Healthy Non-Dominant Limb | P-Value |
|---|---|---|---|
| SLTH Absolute Performance (body heights) | 2.19 ± 0.34 | 2.23 ± 0.40 | 0.721 |
| First Hop Distance (body heights) | 0.67 ± 0.11 | 0.67 ± 0.10 | 0.765 |
| Mean MVIC (nm/kg) | 1.66 ± 0.515 | 1.88 ± 0.639 | 0.277 |
| SLTH Limb Symmetry Index (%) | 96.21 ± 6.32 | 98.82 ± 5.31 | 0.189 |

Ankle, knee, hip, and total extensor moment impulse during the propulsive phase of the hop task are presented in Figure 4. No significant Group*Joint interaction (p=0.528) or Group main (p=0.409) effects were identified for the magnitude of joint extensor impulse during the propulsive phase of the initial hop. However, irrespective of group, the magnitude of ankle plantar flexor impulse was greater than the magnitudes of hip and knee extensor impulse (p<0.001).

Individual joint contributions to TSM are presented in Figure 5. Similar to joint impulse magnitude, no significant Group*Joint interaction (p=0.507) or Group main (p=0. 582) effects were identified for the relative joint contributions to TSM impulse during the propulsive phase of the initial hop. A significant main effect for joint was identified (p<0.001) with the ankle producing a significantly larger contribution to TSM impulse when compared to the knee and hip regardless of prior injury status.

**Figure 4: Individual joint extensor moment impulse and total extensor support moment (TSM) across joints. No significant difference in TSM between groups was identified (*p*>0.05). Similarly, no significant group or group*joint interaction effects were identified (*p*>0.05). However, a significant joint main effect was identified (*p*<0.001). The ankle produced the greatest magnitude of joint moment impulse in comparison to the hip and knee regardless of previous injury status.**

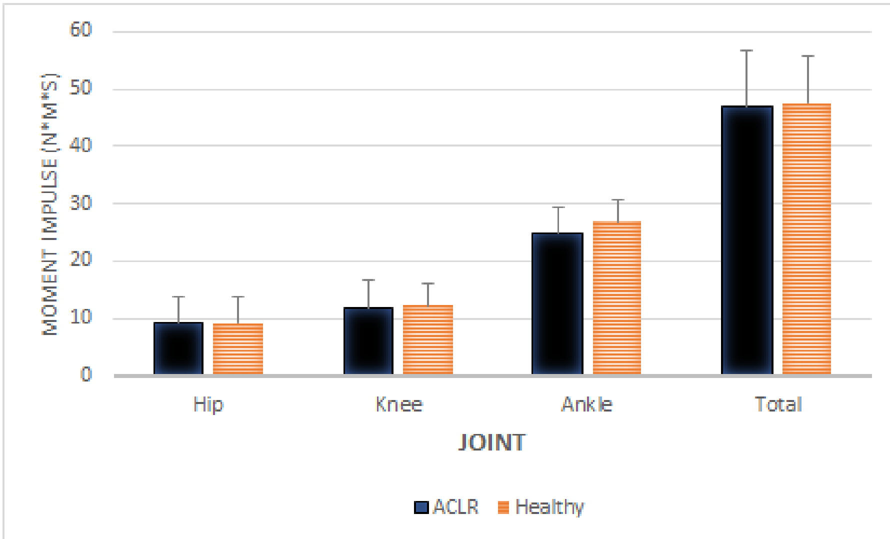
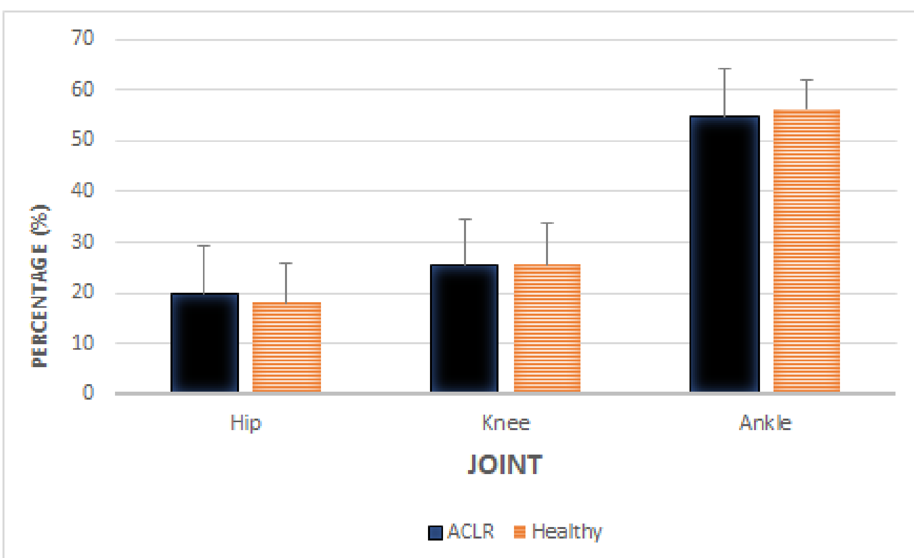



**Figure 5: Joint contributions to the propulsive phase of the hop were broken down by joint with the ankle contributing over half of the performance (~55%). For both groups, the knee only contributed about 26% of the performance. Once again, no significant differences between ACLR or healthy group across joints, indicating the same movement pattern regardless of previous injury status (*p* = 0.582).**



**DISCUSSION**

Our original hypothesis predicted that the ACLR group would use different contributions of their joints when compared to the healthy group, such as using the hip and ankle joints to a greater percentage to compensate for weaker quadriceps. In addition, we predicted they would be able to jump the same distances as the healthy group despite weaker quadriceps due to these compensations. These hypotheses were based on past research which had proposed two main challenges with the single leg triple hop task: 1) an assumption that individuals who have had ACLR can utilize joint compensations to achieve symmetrical task performance, and 2) these compensations undermine the credibility of using the symmetry of hop distances to assess quadriceps strength symmetry (Palmieri-Smith & Lepley, 2015; Barfod, Feller, Hartwig, Devitt, & Webster, 2019; Herbst et al., 2015; Leister et al., 2019; Wellsandt, Failla, & Snyder-Mackler, 2017; Baumgart et al., 2017; Paterno et al., 2014; Ernst, 2000). The results of this study demonstrate that both groups exhibited similar hop performance and quadriceps strength as well as joint contributions to TSM. However, when breaking down the propulsive phase by joint, the ankle produced a significantly greater magnitude of joint moment impulse and a higher joint contribution to overall TSM than the knee or hip, regardless of group. These results were unexpected and contrary to most of our original hypotheses.

Our data showed there was no difference in how the hops were performed between groups, therefore showing that no compensations were present in ACLR participants. The joint extensor impulses – both the magnitude and relative contribution to TSM – were not significantly different between groups and both groups achieved the same overall average hop distance. Our expectation was that hop distance would be similar between groups, but that the healthy population would have greater quadriceps strength and that the ACLR group would therefore need to increase hip and ankle contributions to the propulsive phase of the hop task to compensate for this weakness. However, ACLR participants in this study unexpectedly did not exhibit significantly less quadriceps strength than healthy controls. Rather than this lack of difference in quadriceps strength being the driving factor behind the similar hop performance, we identified that the triple hop test does not place a high demand on the knee extensors for either ACLR or healthy individuals.

Our findings show that regardless of group, the propulsive phase of the hopping task is primarily driven by the ankle and not the knee (Figures 4 and 5). The ankle produced over half of the total impulse contribution, indicating that the plantar flexor muscle group is dominant. These results therefore suggest that the distance completed in this hopping task is not highly related to, nor likely predicative of, quadriceps function. To further explore the relationship between quadriceps strength and triple hop distance, we conducted secondary analyses assessing the relationship between peak quadriceps MVIC and hop distance. We found there was no correlation ($r = 0.038$, $p = 0.877$) between quadriceps strength and initial hop distance in the ACLR group, which supports our previous conclusion that task performance is not driven by the knee extensors. Regardless of how strong or weak the quadriceps were, quadriceps strength could not be used to predict the performance of the hop. However, we did identify that greater quadriceps strength was associated with greater initial hop distance in healthy females ($r = 0.572$, $p = 0.013$). However, we believe that this finding may be due to the fact that the strength of the quadriceps and plantar flexors are highly correlated in healthy individuals (Chang et al., 2015) and that this association may not be as strong after ACLR, such that those ACLR participants with greater quadriceps strength may not have the greatest plantar flexor strength. However, this idea should be evaluated in future studies. Nonetheless, the results for the ACLR participants suggests that practitioners and therapists that use hopping tasks in ACLR patients as a means of inferring quadriceps strength rather than objectively assessing it are likely to incorrectly determine the true status of the patient.

There are some limitations to this study, such as only evaluating the first hop in the triple hop task. While unlikely, it is possible that the participants use a different propulsion strategy during the first hop compared to the following two hops which might reveal the quadriceps are more important for propulsion later on in the task. We also did not control the time from return to sport for the ACLR group beyond requiring that their release had to be within two years of their participation in this study. Additionally, we only included females in this study, so future research should confirm that these results are accurate for both sexes. Finally, it is difficult to compare our results with previous research as past studies have primarily compared hop performance between limbs of the same patient, rather than comparing ACLR performance against a population with no history of knee injuries. By using the non-dominant limb of the healthy participant to contrast with the reconstructed limb of the ACLR participant, we sought to determine what biomechanical differences ACLR participants might exhibit when compared to a group that had never been injured. However, we did not require participants in this study to be active in specific kinds of sports, such as those with high amounts of cutting or pivoting. It is possible that our healthy group participated in sports with lower risk of ACL injury, and are therefore were only considered healthy because they had not been exposed to activities that put them at risk. Future research should consider testing populations from specific sports backgrounds to ensure they have the same athletic background as the ACLR group.

## CONCLUSION/CLINICAL IMPLICATION

The results of this investigation provide evidence that greater performance during a triple hop task is not indicative of greater quadriceps strength in females within two years of return to activity after ACLR. Further, we determined that the reason that quadriceps strength cannot be inferred using a hopping task in individuals following ACLR is because individuals – regardless of previous injury status – primarily utilize the ankle rather than the knee to generate propulsion. This result also suggests that previously identified between-limb symmetries in hop performance in ACLR participants exhibiting quadriceps strength asymmetries is not the result of a compensatory movement strategy on the reconstructed limb to overcome quadriceps weakness.

Future research should evaluate if all variations of single leg hop tests (cross-over hop for distance, 6-m timed hop, etc.) are dependent on the ankle in an effort to identify if any of these other common clinical tests are more reflective of quadriceps strength than the triple hop test. Until then, clinicians should consider the use of tools such as handheld dynamometers to objectively assess quadriceps strength.

**REFERENCES**

Barfod, K. W., Feller, J. A., Hartwig, T., Devitt, B. M., & Webster, K. E. (2019). Knee extensor strength and hop test performance following anterior cruciate ligament reconstruction. *The Knee*, *26*(1), 149–154. https://doi.org/10.1016/j.knee.2018.11.004

Baumgart, C., Schubert, M., Hoppe, M. W., Gokeler, A., & Freiwald, J. (2017). Do ground reaction forces during unilateral and bilateral movements exhibit compensation strategies following ACL reconstruction? *Knee Surgery, Sports Traumatology, Arthroscopy*, *25*(5), 1385–1394. https://doi.org/10.1007/s00167-015-3623-7

Bell, A. L., Pedersen, D. R., & Brand, R. A. (1990). A comparison of the accuracy of several hip center location prediction methods. *Journal of Biomechanics*, *23*(6), 617–621. https://doi.org/10.1016/0021-9290(90)90054-7

Bisseling, R. W., & Hof, A. L. (2006). Handling of impact forces in inverse dynamics. *Journal of Biomechanics*, *39*(13), 2438–2444. https://doi.org/10.1016/j.jbiomech.2005.07.021

Chang, E., Norcross, M. F., Johnson, S. T., Kitagawa, T., & Hoffman, M. (2015). Relationships between explosive and maximal triple extensor muscle performance and vertical jump height. *Journal of Strength and Conditioning Research*, *29*(2), 545–551. https://doi.org/10.1519/JSC.0000000000000652

Chang, E. W., Johnson, S., Pollard, C., Hoffman, M., & Norcross, M. (2018). Landing biomechanics in anterior cruciate ligament reconstructed females who pass or fail a functional test battery. *The Knee*, *25*(6), 1074–1082. https://doi.org/10.1016/j.knee.2018.09.006

Davies, G. J., McCarty, E., Provencher, M., & Manske, R. C. (2017). ACL return to sport guidelines and criteria. *Current Reviews in Musculoskeletal Medicine*, *10*(3), 307–314. https://doi.org/10.1007/s12178-017-9420-9

Ernst, G. P. (2000). Lower-extremity compensations following anterior cruciate ligament reconstruction. *Physical Therapy*, *80*(3), 251–260.

Gagnon, D., & Gagnon, M. (1992). The influence of dynamic factors on triaxial net muscular moments at the L5S1 joint during asymmetrical lifting and lowering. *Journal of Biomechanics*, *25*(8), 891–901. https://doi.org/10.1016/0021-9290(92)90229-T

Garber, C. E., Blissmer, B., Deschenes, M. R., Franklin, B. A., Lamonte, M. J., Lee, I.-M., Nieman, D. C., Swain, D. P., & American College of Sports Medicine. (2011). American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: Guidance for prescribing exercise. *Medicine and Science in Sports and Exercise*, *43*(7), 1334–1359. https://doi.org/10.1249/MSS.0b013e318213fefb

Gornitzky, A. L., Lott, A., Yellin, J. L., Fabricant, P. D., & Ganley, T. J. (2017). Sport-specific yearly risk and incidence of anterior cruciate ligament tears in high school athletes: A systematic review and meta-analysis. *Pediatrics*, *140*(1 MeetingAbstract), 109–109. https://doi.org/10.1542/peds.140.1_MeetingAbstract.109

Grindem, H., Snyder-Mackler, L., Moksnes, H., Engebretsen, L., & Risberg, M. A. (2016). Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: The Delaware-Oslo ACL cohort study. *British Journal of Sports Medicine*, *50*(13), 804–808. https://doi.org/10.1136/bjsports-2016-096031

Herbst, E., Hoser, C., Hildebrandt, C., Raschner, C., Hepperger, C., Pointner, H., & Fink, C. (2015). Functional assessments for decision-making regarding return to sports following ACL reconstruction. Part II: Clinical application of a new test battery. *Knee Surgery, Sports Traumatology, Arthroscopy*, *23*(5), 1283–1291.

Herrington, L., Ghulam, H., & Comfort, P. (2018). Quadriceps strength and functional performance after anterior cruciate ligament reconstruction in professional soccer players at time of return to sport. *Journal of Strength and Conditioning Research*, 1. https://doi.org/10.1519/JSC.0000000000002749

Hoffman, M., Schrader, J., Applegate, T., & Koceja, D. (1998). Unilateral postural control of the functionally dominant and nondominant extremities of healthy subjects. *Journal of Athletic Training*, *33*(4), 319–322.

Huang, Y.L. (2019). The influence of quadriceps rate of torque development and arthrogenic muscle inhibition on knee landing mechanics during different landing tasks in ACL reconstructed females [Unpublished doctoral dissertation]. Oregon State University.

Leister, I., Kulnik, S. T., Kindermann, H., Ortmaier, R., Barthofer, J., Vasvary, I., Katzensteiner, K., & Mattiassich, G. (2019). Functional performance testing and return to sport criteria in patients after anterior cruciate ligament injury 12–18 months after index surgery: A cross-sectional observational study. *Physical Therapy in Sport*, *37*, 1–9. https://doi.org/10.1016/j.ptsp.2019.01.010

Palmieri-Smith, R. M., & Lepley, L. K. (2015). Quadriceps strength asymmetry after anterior cruciate ligament reconstruction alters knee joint biomechanics and functional performance at time of return to activity. *The American Journal of Sports Medicine*, *43*(7), 1662–1669. https://doi.org/10.1177/0363546515578252

Paterno, M. V., Rauh, M. J., Schmitt, L. C., Ford, K. R., & Hewett, T. E. (2014). Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport. *The American Journal of Sports Medicine*, *42*(7), 1567–1573. https://doi.org/10.1177/0363546514530088

Paterno, M. V., Rauh, M. J., Schmitt, L. C., Ford, K. R., & Hewett, T. E. (2012). Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clinical Journal of Sport Medicine: Official Journal of the*

*Canadian Academy of Sport Medicine*, *22*(2), 116–121. https://doi.org/10.1097/JSM.0b013e318246ef9e

Pietrosimone, B., McLeod, M. M., Florea, D., Gribble, P. A., & Tevald, M. A. (2015). Immediate increases in quadriceps corticomotor excitability during an electromyography biofeedback intervention. *Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology*, *25*(2), 316–322. https://doi.org/10.1016/j.jelekin.2014.11.007

Thomeé, R., Kaplan, Y., Kvist, J., Myklebust, G., Risberg, M. A., Theisen, D., Tsepis, E., Werner, S., Wondrasch, B., & Witvrouw, E. (2011). Muscle strength and hop performance criteria prior to return to sports after ACL reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy: Official Journal of the ESSKA*, *19*(11), 1798–1805. https://doi.org/10.1007/s00167-011-1669-8

Wellsandt, E., Failla, M., & Snyder-Mackler, L. (2017). Limb symmetry indexes can overestimate knee function after ACL injury. *The Journal of Orthopaedic and Sports Physical Therapy*, *47*(5), 334–338. https://doi.org/10.2519/jospt.2017.7285