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Walking Ground Reaction Force Post-ACL Reconstruction: Analysis of Time and Symptoms

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Abstract

Purpose: The association between lower-extremity loading and clinically-relevant knee symptoms at different time points following anterior cruciate ligament reconstruction (ACL) is unclear. Vertical ground reaction force (vGRF) from walking was compared between individuals with and without clinically-relevant knee symptoms in three cohorts: <12 months post-ACL, 12–24 months post-ACL, and >24 months post-ACL.

Methods: 128 individuals with unilateral ACL were classified as symptomatic or asymptomatic, based on previously-defined cutoff values for the Knee Osteoarthritis and Injury Outcome Score (<12 months post-ACL [symptomatic n=28, asymptomatic n=24]; 12–24 months post-ACL [symptomatic n=15, asymptomatic n=15], and >24 months post-ACL [symptomatic n=13, asymptomatic n=33]). vGRF exerted on the ACL limb was collected during walking gait, and functional analyses of variance were used to evaluate the effects of symptoms and time post-ACL on vGRF throughout stance phase ($\alpha=0.05$).

Results: Symptomatic individuals, <12 months post-ACL, demonstrated less vGRF during both vGRF peaks (i.e. weight acceptance and propulsion) and greater vGRF during midstance, compared to asymptomatic individuals. vGRF characteristics were not different between symptomatic and asymptomatic individuals for most of stance in individuals between 12 and 24 months post-ACL. Symptomatic individuals who were >24 months post-ACL, exhibited greater vGRF during both peaks, but lesser vGRF during midstance, compared to asymptomatic individuals.

Conclusion: Relative to asymptomatic individuals, symptomatic individuals are more likely to underload the ACL limb early following ACL (i.e., <12 months) during both vGRF peaks, but overload the ACL limb, during both vGRF peaks, at later time points (i.e., >24 months). We

propose these differences in lower extremity loading during walking might have implications for long-term knee health, and should be considered when designing therapeutic interventions for individuals with an ACLR.

Keywords

Anterior Cruciate Ligament; KOOS; Posttraumatic Osteoarthritis; Biomechanics; Walking

Introduction

Forty percent of individuals continue to report clinically relevant knee symptoms, based on the Knee Injury and Osteoarthritis Outcome survey (KOOS), two years post-ACLR.(1) Poor patient reported outcomes might reflect underlying joint tissue changes related to poor long-term knee health. Specifically, lower KOOS scores are associated with magnetic resonance imaging outcomes related to altered femoral cartilage composition 12 months after ACLR, (2) suggesting worse patient-reported outcomes may be related to the early development of posttraumatic osteoarthritis (PTOA). Furthermore, persistent knee symptoms are associated with chronic abnormal loading of the lower extremity,(3, 4) potentially hastening deleterious changes in joint tissues.(5–8) Unfortunately, the association between lower extremity loading and persistent clinically relevant knee symptoms is unclear.

Evidence from animal models clearly demonstrates that both excessive(9) and insufficient mechanical loading(10, 11) can cause deleterious changes to weight bearing joints. Greater impulsive loading has been demonstrated in the ACLR limb compared to the contralateral limb,(12) as well as a matched limb of uninjured controls(13) in two cohorts of females a mean of approximately 4 and 5 years post-ACLR, respectively. Conversely, lesser loading of the ACLR limb in the first 6 months following ACLR is associated with deleterious changes in biomarkers of cartilage metabolism at 6 months post-ACLR,(14) worse patient reported outcomes 12 months post-ACLR,(3) and a greater likelihood of radiographic PTOA 5 years post-ACLR.(15) Overall, the available evidence regarding the association between lower-extremity joint loading and knee joint health is contradictory, and additional research is needed to clarify the association between lower-extremity loading and patient-reported outcomes at various time points after ACLR (e.g., <12 months, 12–24 months, and >24 months). A greater understanding of how movement strategies differ between symptomatic and asymptomatic individuals with ACLR is critical for developing treatments to optimize gait biomechanics post ACLR. Additionally, the influence of time since ACLR on joint loading in individuals with and without clinically relevant symptoms is unknown.

The primary purpose of this cross-sectional study was to compare walking vGRF applied to the ACLR limb, throughout the stance phase, between individuals with and without clinically relevant knee symptoms at multiple time-points following ACLR. Comparisons were made between three cross-sectional cohorts separated into clinically relevant time periods: 1) <12 months post-ACLR, 2) between 12 and 24 months post-ACLR, and 3) >24 months post-ACLR. We defined clinically relevant knee symptoms based on previously defined cutoff scores for the KOOS.(16) vGRF is a fundamental measure of lower extremity loading during gait. Discrete measures related to vGRF during gait (i.e., peak vGRF and the

corresponding vGRF load rate) have been linked to knee joint health outcomes, including biochemical markers of joint metabolism,(14, 17) cartilage composition,(18) and patient reported outcomes.(3) However, assessing discrete vGRF characteristics provides a limited evaluation of forces acting on the lower extremity loading during stance. Analysis of the vGRF time series waveform, throughout the stance phase of gait, likely provides a more comprehensive indicator of lower-extremity loading. Therefore, we hypothesized individuals <12 months post-ACLR, with clinically relevant knee symptoms, would demonstrate less vGRF, throughout stance, compared to individuals without clinically relevant knee symptoms. In individuals between 12 and 24 months post-ACLR, and >24 months post-ACLR, we hypothesized that individuals with clinically relevant knee symptoms would demonstrate greater vGRF throughout stance, relative to individuals without clinically relevant knee symptoms.

Methods

Participants were recruited into a combined cross-sectional study (N=128; Table 1) leveraging multiple ongoing studies, including a separate cross-sectional project (n=36), prospective longitudinal ACL cohort study (n=36), and randomized controlled trial (n=56) evaluating the immediate effects of vibration therapy on individuals with an ACLR (NCT02605876). All data in the current study were collected prior to any intervention and the same protocols, as well as equipment were used to collect gait biomechanics and KOOS data for all participants. For the current study, all participants performed the gait analysis during a single session and were separated into time post-ACLR cohorts based on the number of months post-ACLR at the time of the analysis. All participants provided informed consent approved by the Institutional Review Board at the University of North Carolina at Chapel Hill prior to participation in any research related procedures.

Participants

Individuals between the ages of 18 and 35 years who sustained a unilateral ACL injury and underwent ACLR were included (Table 1). Individuals with any of the following were excluded: history of any other lower extremity orthopaedic surgery, ACLR revision surgery, multi-ligament reconstruction at the time of ACLR, physician diagnosed knee osteoarthritis (radiographically diagnosed or diagnosed based on symptoms), balance or neuromuscular disorders, or history of an orthopaedic injury in either limb during six months prior to testing.(12, 17) Potential participants were recruited from university health system orthopaedic clinics, university club sport teams, university varsity athletics, and the general university community.

Vertical Ground Reaction Force Acquisition

Prior to gait analysis, participants were outfitted with retroreflective markers, including a rigid cluster of three markers over the sacrum used to determine walking speed, as previously described.(24) Marker positions were quantified using a 10-camera 3D motion capture system (120 Hz) and Vicon Nexus v1.4.1 software (Vicon Motion Systems, Santa Rosa, CA, USA). Marker trajectories were lowpass filtered at 10 Hz (4th order recursive Butterworth), and vGRF data were sampled at 1200 Hz and lowpass filtered at 75 Hz (4th

order recursive Butterworth). For each of the five acceptable walking trials, vGRF data during the stance phase for the involved limb, defined as the interval between heel strike ($vGRF > 20$ N) and toe off ($vGRF < 20$ N), were extracted and time normalized to 100% of stance phase using 500 data points, as well as normalized to body weight for each subject; this processing was performed using custom algorithms in MATLAB (version R2017A, MathWorks, Natick, MA, USA).

Participants walked barefoot at a self-selected speed (Table 1) over a 40×60 cm force plate (FP406010, Bertec Corporation, Columbus, Ohio, USA) embedded in a 6-m walkway. Participants were instructed to walk as if they were “comfortably walking over a sidewalk” while looking straight ahead and maintaining a constant speed through two sets of timing gates (TF100, Trac Tronix, Lenexa, Kansas, USA). Participants were allowed as much time as necessary to acclimate to walking in the lab. Once the participants indicated they felt comfortable with the marker setup, they performed five practice trials used to further familiarize the participants with the gait task and determine the self-selected walking speed. During data collection, participants performed five acceptable gait trials, which required participants to: (1) place the entire foot on the force plate, (2) maintain forward eye contact (not aim for the force plate), (3) walk within 5% of the aforementioned self-selected speed, and (4) not visibly alter gait during the trial (i.e., no trip or stutter step).^(14, 17, 19)

Knee Injury and Osteoarthritis Outcomes Score (KOOS)

We used the five subscales of the KOOS to assess pain (KOOS Pain), symptoms (KOOS Symptoms), function in activities of daily living (KOOS ADL), function in activities of sport and recreation (KOOS Sport), and knee-related quality of life (KOOS QOL).⁽²⁰⁾ All KOOS subscales demonstrate acceptable reliability (ICCs = 0.75–0.96) and construct validity compared to the Short Form-36 questionnaire in individuals with an ACLR.⁽²¹⁾ The KOOS was electronically scored to minimize processing error and each subscale was normalized to 100%, which was considered the best possible score for each subscale of the KOOS, such that higher scores indicated better patient-reported outcomes.

Based on a previous definition,⁽¹⁶⁾ participants were dichotomized into those with clinically relevant knee symptoms following ACLR and those with acceptable outcomes at the twelve-month follow-up exam. Individuals who reported KOOS QOL ≥ 87.5 , and met two or more of the other 4 subscales cut-off values (KOOS Symptoms ≥ 85.7 ; KOOS Pain ≥ 86.1 ; KOOS ADL ≥ 86.8 , KOOS Sports ≥ 85.0) were considered to demonstrate clinically relevant knee symptoms.⁽¹⁶⁾ We considered individuals who were not categorized as demonstrating clinically significant knee symptoms as asymptomatic. Approximately 43% (N=1530) and 39% (N=1506) of the individuals enrolled in the Multicenter Orthopaedic Outcomes Network (MOON) Knee Project cohort demonstrated clinically significant knee symptoms using the same criteria at 2 and 6 years following ACLR, respectively.⁽¹⁾ The present participants (n = 128) were divided into symptomatic and asymptomatic groups, based on (1) KOOS scores, and (2) time (months) post-ACLR (Table 1).

Statistical Analysis

Prior to our primary analyses, potential differences in discrete demographic variables (Table 1) between the symptomatic and asymptomatic participants for each of the different post-ACLR cohorts were evaluated using independent t-tests ($\alpha=0.05$; SPSS, Version 19.0, IBM Corp., Somers, NY, USA). Next, 2×2 functional analyses of variance(22) were used to evaluate the effects of group (symptomatic and asymptomatic) and time post-ACLR cohort (<12 months, 12–24 months, and >24 months) on the time-normalized vGRF waveform. The functional approach facilitated comparison of vGRF magnitude at each percentile of the stance phase rather than only at certain discrete time points. The vGRF ensemble averages were plotted for the symptomatic and asymptomatic groups in the different post-ACLR cohorts with corresponding 95% confidence intervals. The functional analyses of variance were performed using the functional data analysis package in R statistical computing software (version 3.4.3) to compute mean differences and corresponding 95% confidence intervals between symptomatic and asymptomatic ensemble averages at each percent of stance. The symptomatic and asymptomatic groups were considered different at any percentile of the stance phase where mean differences and corresponding 95% confidence intervals did not cross zero. (22)

Results

Mean age and stance duration were significantly greater in the asymptomatic individuals compared to the symptomatic individuals in the >24 month post-ACLR cohort (Table 1). No other demographic differences were found between symptomatic and asymptomatic groups in each cohort.

Statistical differences for vGRF existed between the symptomatic and asymptomatic individuals at various times throughout the stance phase for each cohort (<12 months, 12–24 months, and >24 months post-ACLR). For the <12 months cohort, vGRF was an average mean difference up to 0.05 BW less for the symptomatic group, between 10 and 22%, and between 68 and 90% of stance, but greater (an average mean difference up to 0.03 BW more) between 32 and 53% of stance (Figure 1D). For the 12–24 months cohort, differences in vGRF were only found between the symptomatic and asymptomatic groups between 85 and 100% of stance (symptomatic group was greater; Figure 1E). vGRF was up to 0.07 BW greater for the symptomatic individuals in the >24 months cohort, between 2 and 5%, 15 and 32%, and 68 and 89% of stance, but up to 0.07 BW less between 39 and 62% of stance (Figure 1F).

Differences between symptomatic and asymptomatic individuals varied among the three cohorts (Figure 2). Figure 2A illustrates an interaction between group (i.e., symptomatic and asymptomatic individuals) and cohorts (i.e. <12 months and 12–24) during 32 – 58%, and 73 – 99% of stance. Primarily, between-group differences existed for the <12 months cohort, but not for the 12–24 month post-ACLR cohort. Similarly, Figure 2B demonstrates an interaction between group (i.e. symptomatic and asymptomatic) and cohorts (i.e. 12–24 months and >24 months) during 18 – 34%, 43 – 57%, 68 – 79%, and 93–99% of stance. During these percentages of stance, primarily, between-group differences existed for the >24 months post-ACLR cohort but not for the 12–24 months post-ACLR cohort.

Differences between cohorts were more substantial for the symptomatic individuals compared to the asymptomatic individuals (Figures 3–5). When comparing symptomatic individuals in the <12 months and 12–24 months cohorts, the symptomatic individuals in the <12 months cohort exhibited less vGRF (average mean difference as much as 0.06 BW less; between group effect size Cohen's $d=-0.599$) between 0 and 26% of stance, and throughout the majority of the final 26% of stance. Additionally, there was an average mean difference as much as 0.04 BW ($d=0.613$) greater vGRF between 34 and 65% of stance in symptomatic individuals in the <12 months compared to the symptomatic 12–24 months cohort (Figure 3C). When comparing symptomatic individuals in the 12–24 months and >24 months cohorts, the symptomatic individuals in the 12–24 month cohort exhibited an average mean difference as much as 0.05 BW less vGRF ($d=-0.642$) between 15 and 32%, and 67 and 86% of stance, and as much as 0.05 BW greater vGRF ($d=0.506$) between 40 and 57% of stance (Figure 3D). The asymptomatic individuals exhibited relatively fewer differences between post-ACLR cohorts (Figure 4). vGRF differed only between 5 and 8% (about 0.04 BW; $d=-0.348$) and between 92 and 97% (about 0.03 BW; $d=0.382$) of stance when comparing the <12 months and 12–24 months cohorts (Figure 4C). Similarly, vGRF for the asymptomatic individuals differed only between 27 and 35% (about 0.02 BW; $d=0.331$) and 92 and 98% (about 0.03 BW; $d=-0.393$) of stance, when comparing the 12–24 months and >24 months cohorts (Figure 4D). Figures 5A and 5B illustrate mean vGRF plots for symptomatic and asymptomatic groups for each post-ACLR cohort, and further demonstrate the symptomatic individuals differed relatively more, between the three cohorts, compared to the asymptomatic individuals.

Discussion

Consistent with our hypothesis, we found differences in vGRF between symptomatic and asymptomatic individuals for each post-ACLR cohort, and the direction of these differences varied depending upon time post-ACLR (Figure 1). This is the first study to demonstrate this type of interaction, for walking vGRF between symptomatic and asymptomatic individuals, across different time points post-ACLR. Overall, the data demonstrate a tendency for clinically symptomatic ACLR patients, <12 months post-ACLR, to underload the ACLR limb during the weight acceptance and propulsive aspects of stance (i.e., the first and final third of stance), relative to asymptomatic counterparts; conversely, the clinically symptomatic patients who were >24 months post-ACLR overloaded the ACLR limb during the weight acceptance and propulsion periods of stance (Figures 1A, 1C, 1D, and 1F). These findings support the notion that mechanical loading of the lower extremity is associated with clinically relevant knee symptoms post ACLR, and the association may be influenced by time post-ACLR. Previous literature is equivocal regarding whether excessive or insufficient loading contributes to post-ACLR knee joint health, and the present data suggest that both excessive and insufficient loading might influence post-ACLR knee joint health. Given the link between persistent clinically relevant symptoms for post-ACLR patients and negative changes in joint health,(2, 23) these findings provide insight into loading patterns which associate with poorer clinical outcomes in separate cohorts of individuals at different times post-ACLR.

At the beginning of stance, vGRF rapidly increases at its greatest rate to the first vGRF peak. This weight acceptance phase of gait results in substantial load applied to the lower extremity, including the knee. Peak vGRF in the first 6 months post-ACLR associate with multiple aspects of knee joint health including, serum biochemical markers of cartilage metabolism at the same time point,(14) self-reported function at 12 months post ACLR,(3) and tibiofemoral compositional changes at 2 years post-ACLR.(18) Therefore, differences in vGRF between symptomatic and asymptomatic individuals during the beginning of stance may be critical for understanding chronic changes in knee joint health. For each of the three cohorts, differences existed between symptomatic and asymptomatic subjects during the first third of stance; therefore, symptomatic individuals were experiencing different loads applied to the ACLR limb shortly after ground contact, relative to asymptomatic counterparts. It may also be important to consider vGRF throughout the final two thirds of stance phase of gait in addition to the weight acceptance portion of stance. The midstance phase of gait has been referred to as the unloading phase because vGRF at this time is less than the weight acceptance and propulsive peaks. Our findings indicated symptomatic individuals who were <12 months post-ACL, demonstrated greater vGRF during midstance, while symptomatic individuals who were >24 months post-ACLR demonstrated decreased vGRF during midstance. Loading of the limb during midstance may be critical for optimizing joint tissue mechanics, and maintaining overall cartilage health, however, further research is necessary to determine how changes in midstance loading impacts knee health. The vGRF waveform characterized by (1) decreased weight acceptance vGRF peak, but (2) greater vGRF during midstance in symptomatic individuals <12 months post-ACLR found in our study is similar to individuals experiencing pain-induced kinesiphobia.(24) It is possible pain-related fear of movement may play a role in the altered movement patterns found between those with and without symptoms in the first 12 months following ACLR. Yet, recent work has found kinesiphobia does not associate with peak gait mechanics in the first 50% of stance in individuals with an ACLR,(25) suggesting that fear of pain with movement may not have a strong influence on limb loading during walking in individuals who have returned to unrestricted activity. Abnormal vGRF during any part of stance, including the middle and final third could detrimentally influence knee joint health,(26, 27) and should be quantified in this context, throughout the stance phase, rather than only during impact loading. The present statistical approach (functional analysis of variance) allowed for the detection of differences in vGRF throughout stance, including the middle and final thirds of the stance phase, which have been studied to a lesser magnitude in this context. Thus, we contend the present analytical approach provides a more comprehensive assessment of loading, relative to assessment of vGRF magnitudes only at discrete time points (e.g. peak vGRF).

Excessive(9) and/or insufficient loading(10, 11) can influence deleterious changes to joint tissue health, yet definitive identification of specific biomechanical variables associated with poor clinical outcomes, post-ACLR, lacks. It has long been hypothesized that greater mechanical loading of the knee is the mechanism leading to poor long-term outcomes and early osteoarthritis onset.(28–30) Although existing evidence supports this hypothesis, related literature is inconsistent. Females with ACLR, with a mean of 4–5 years post-ACLR, demonstrate greater peak vGRF and vGRF load rates in the ACLR limb, relative to the contralateral limb(12) and matched limbs of uninjured controls.(13) Likewise, greater peak

vGRF during gait is associated with deleterious changes in cartilage composition 24 months following ACLR.(18) Conversely, lesser vGRF-loading rate and knee abduction moment, six months following ACLR, are each associated with greater serum biomarkers of inflammation and degenerative cartilage enzymes.(14) Also, individuals who developed PTOA five years following ACLR demonstrated decreased knee contact force at a 6-month follow-up compared to those who did not develop PTOA.(15) The present results may partially explain these contradictions and support the ideas that abnormal biomechanics, in the ACLR limb, are (1) related to clinical outcomes, and (2) vary over time post-ACLR. It is important to further evaluate mechanisms leading to changes in loading following ACLR. While not statistically different, symptomatic individuals (1.31 ± 0.26) walked faster than asymptomatic counterparts (1.18 ± 0.19 ; See Table) in the >24 month post-ACLR cohort during gait analysis, which may partially explain greater loading during stance phase(31) and the statistically lesser stance duration in the symptomatic group (See Table). Slower habitual walking speeds are predictive of incident idiopathic knee osteoarthritis(32) and greater serum concentrations of type-II collagen breakdown(19) and higher T1rho magnetic resonance imaging relaxation times associated with lesser femoral cartilage proteoglycan density(33) in individuals with an ACLR. It is possible greater walking speeds may be an adaptive response by symptomatic individuals to protect underlying joint tissues, as shorter stance phases during faster gait speeds may result in lesser compression of viscoelastic structures such as articular cartilage.(34) The results of the present study imply a progression, from underloading to overloading, for clinically symptomatic patients post ACLR (Figures 1 & 5); yet longitudinal research is needed to confirm these hypotheses, as well as determine if underloading or overloading results in long-term deleterious changes in joint health.

Our cross-sectional study design is unable to determine causality between altered walking vGRF and clinically related knee symptoms. It is possible symptomatic individuals underload the ACLR limb early following ACLR (Figure 1A) an attempt to alleviate symptoms. It is also possible that early underloading of the ACLR limb is due to inadequate neuromuscular control(35) or impaired proprioception.(36) In a recent study evaluating peak vGRF in the first 50% of the stance phase of gait,(3) individuals with more asymmetrical underloading 6 months post-ACLR (lesser peak vGRF in the ACLR limb compared to the uninjured limb) demonstrated worse KOOS scores 12 months post-ACLR, suggesting early altered loading may influence worse patient reported outcomes at later follow ups. We can further hypothesize, overtime, insufficient loading of the ACLR limb may signal deleterious changes in joint tissues,(11) and manifest in increased knee symptoms. Similarly, mechanisms related to greater vGRF peaks at later time points (e.g., >24 months) in symptomatic individuals are unclear, yet we hypothesize that these increases in vGRF may also be caused by neuromuscular or proprioceptive impairments influencing the inability to control and attenuate energy directed toward the lower extremity during gait.(37, 38) It remains unknown why symptomatic individuals < 12 months underload the ACLR limb, while symptomatic individuals >24 months overload the ACLR limb compared to asymptomatic counterparts; yet, mechanisms related to early underloading may be associated to later overloading. It is possible symptoms may lead to aberrant loading early following ACLR while aberrant loading may further perpetuate the development of

symptoms at later time points (e.g., >24 months post-ACLR). Future longitudinal studies are needed to determine the precise causes of altered lower extremity biomechanics, at multiple time points after ACLR, in symptomatic and asymptomatic individuals.

The current study is novel and important, yet some additional limitations exist and should be highlighted to inform future research. First, we did not evaluate the influence of concomitant injury (i.e. meniscal injury) or graft type on differences in vGRF between symptomatic and asymptomatic individuals. Future, larger scale studies should determine the effects of concomitant injury and graft selection in this context. Similarly, participants in our study sustained a unilateral ACL injury, and we are unable to generalize our results to individuals with multiple ACL injuries. We have presented data describing barefoot gait at a self-selected walking speed and future research should evaluate shod walking, as well as other movement patterns, including movements involving greater vGRF (e.g., running, jumping and landing). Future research should also evaluate activities of daily living in the real world (i.e., outside of the lab). Although vGRF is a fundamental measure of lower extremity loading and associated with compositional,(18) structural(15) and self-reported(3) aspects of knee joint health, vGRF cannot specifically describe magnitudes or locations of forces absorbed by specific knee joint structures. Further research is needed to determine if differences in walking vGRF correspond with differences in joint-specific biomechanical parameters (e.g., knee joint kinematics and kinetics), as well as critical discrete biomechanical variables within the waveform analysis (e.g., peak vGRF and vGRF loading rate). The focus of the current study was to evaluate differences in vGRF between symptomatic and asymptomatic individuals with an ACLR; future work evaluating interlimb asymmetries, for symptomatic and asymptomatic individuals, would further elucidate the issues addressed in the present study. Finally, although the present separation of participants into symptomatic and asymptomatic individuals was novel, we do not know whether the symptomatic individuals in the current study will develop PTOA or chronic disability.

In conclusion, vGRF differs between clinically symptomatic and asymptomatic individuals, post-ACLR, and these differences vary depending upon time post-ACLR. Within the <12 months post-ACLR cohort, symptomatic individuals demonstrated less vGRF during approximately the first and last thirds of stance, but greater vGRF during the midstance phase of gait, relative to asymptomatic individuals. Within the 12–24 months post-ACLR cohort, vGRF was relatively similar between the symptomatic and asymptomatic individuals. For the >24 months post-ACLR cohort, symptomatic individuals applied greater vGRF during the first and second vGRF peaks, but less vGRF during midstance, relative to the asymptomatic individuals. These differences may influence chronic knee joint health for post-ACLR patients, and should be considered when designing and evaluating interventions aimed at manipulating load applied to the post-ACLR knee.

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Figure 1. Vertical Ground Reaction Force Differences between Symptomatic and Asymptomatic Individuals In Three Cohorts

Subplots A-C depict mean ensemble waveforms and corresponding 95% confidence intervals, plotted over the stance phase of walking, for mean vertical ground reaction force (vGRF), normalized to body weight (BW), for symptomatic and asymptomatic individuals with an anterior cruciate ligament reconstruction (ACLR) in three different cohorts based on time post-ACL (<12 months—1A, 12–24 months—1B, and >24 months post-op—1C). Vertical shaded bands in Subplots 1A – 1C represent percentages in the stance phase where symptomatic and asymptomatic ensemble means differ based on the corresponding functional comparisons in Subplots 1D-1F. Subplots 1D-1F show corresponding pairwise comparison functions, and associated 95% confidence intervals (gray bands), indicating the mean differences between the symptomatic and asymptomatic groups for the VGRF (although excluded to increase clarity, the precise mean difference is always exactly between the upper and lower 95% confidence interval). For Subplots 1D-1F, the mean differences (vertical axis) represent the symptomatic mean minus the asymptomatic mean at each percentile of the stance phase. Significant between-group differences existed whenever the 95% confidence intervals did not overlap zero.

Figure 2. Vertical Ground Reaction Force Symptom by Cohort Interactions Throughout Stance. Figure 2A depicts differences between group (symptomatic and asymptomatic individuals) and <12 months post-anterior cruciate ligament reconstruction [ACLR] and 12–24 months post-ACLR cohorts. Figure 2B depicts the interaction between group (symptomatic and asymptomatic individuals) and 12–24 months post-ACLR and > 24 months post-ACLR cohorts. Significant group $\times$ cohort interactions existed where the 95% confidence intervals did not overlap zero, indicating that the between group differences differed between cohorts.

Figure 3. Differences in Symptomatic Individuals between Cohorts

Figure 3A depicts mean ensemble waveforms and corresponding 95% confidence intervals, plotted over the stance phase of walking, for mean vertical ground reaction force (vGRF), normalized to body weight (BW), for symptomatic individuals with an anterior cruciate ligament reconstruction (ACLR), in the <12 months post-ACLR cohort and 12–24 months post-ACLR cohort. Figure 3B depicts a similar comparison, except for the considered cohorts are: 12–24 months and >24 months post-ACLR. Vertical shaded bands in Subplots 3A and 3B percentages in the stance phase where ensemble means differ based on the corresponding functional comparisons in Subplots 3C and 3D. Figures 3C and 3D depicts corresponding pairwise comparison functions, and associated 95% confidence intervals (gray bands), indicating the mean differences between the two cohorts, for the VGRF. For Figures 3C and 3D, significant between-symptom group differences existed whenever the 95% confidence intervals did not overlap zero (although excluded to increase clarity, the precise mean difference is always exactly between the upper and lower 95% confidence interval). Walking vGRF significantly differed, across a large majority of the stance phase, when comparing <12 months and 12–24 months, and 12–24 months and >24 months post-ACLR cohorts.

Figure 4. Differences in Asymptomatic Individuals between Cohorts

Figure 4A depicts mean ensemble waveforms and corresponding 95% confidence intervals, plotted over the stance phase of walking, for mean vertical ground reaction force (vGRF), normalized to body weight (BW), for asymptomatic individuals with an anterior cruciate ligament reconstruction (ACLR), in the <12 months post-ACLR cohort and 12–24 months post-ACLR cohort. Figure 3B depicts a similar comparison, except the considered cohorts are: 12–24 months and >24 months post-ACLR. Vertical shaded bands in Subplots 4A and 4B percentages in the stance phase where ensemble means differ based on the corresponding functional comparisons in Subplots 4C and 4D. For Figures 4C and 4D, significant between-symptom group differences existed whenever the 95% confidence intervals did not overlap zero (although excluded to increase clarity, the precise mean difference is always exactly between the upper and lower 95% confidence interval). Walking vGRF significantly differed, across a large majority of the stance phase, when comparing <12 months and 12–24 months, and 12–24 months and >24 months post-ACLR cohorts.

Figure 5. Vertical ground reaction force in Symptomatic and Asymptomatic Individuals in All Cohorts

Mean ensemble plots for vertical ground reaction force (vGRF), time normalized to the stance phase of walking and normalized to body weight (BW), for the symptomatic (5A) and asymptomatic (5B) individuals for the months post- anterior cruciate ligament reconstruction (ACLR) cohorts. Measures of variance were omitted here to enhance clarity, and were comparable between the plotted curves. The symptomatic individuals differed more, between the three cohorts, relative to the asymptomatic individuals.

Table 1.

Participant Demographics and Knee Injury and Osteoarthritis Subscale Scores

	<12 Months Post-ACLR Cohort		12–24 Months Post-ACLR Cohort		>24 Months Post-ACLR Cohort	
	Symptomatic	Asymptomatic	Symptomatic	Asymptomatic	Symptomatic	Asymptomatic
n	28	24	15	15	13	33
Number of Females (%)	16 (57.1%)	14 (58.3%)	11 (73.3%)	10 (66.7%)	13 (100%)	22 (66.7%)
Age (Years)	21.61 ± 3.28	21.75 ± 4.21	20.33 ± 3.16	21.67 ± 4.01	19.77 ± 1.53	21.12 ± 2.27 *
Height (m)	1.74 ± 0.14	1.73 ± 0.11	1.69 ± 0.10	1.72 ± 0.10	1.68 ± 0.08	1.70 ± 0.10
Mass (kg)	75.31 ± 13.95	75.71 ± 16.77	67.19 ± 16.99	75.94 ± 21.67	67.91 ± 8.14	72.84 ± 18.75
BMI (kg/m²)	24.9 ± 3.96	25.01 ± 4.01	23.40 ± 3.57	25.35 ± 4.24	24.19 ± 3.29	24.89 ± 4.51
Graft Type	PT=28 (100%) H=0 (0%) A=0 (0%) QT=0 (0%)	PT=21 (87.5%) H=2 (8.3%) A=1 (4.2%) QT=0 (0%)	PT=10 (66.7%) H=5 (33.3%) A=0 (0%) QT=0 (0%)	PT=7 (46.7%) H=6 (40%) A=0 (0%) QT=2 (13.3%)	PT=6 (46.2%) H=6 (46.2%) A=1 (7.6%) QT=0 (0%)	PT=18 (54.5%) H=10 (30.3%) A=5 (15.2%) QT=0 (0%)
Meniscal Injury	Yes=21 (75%) No=7 (25%)	Yes=14 (58.3%) No=10 (41.7%)	Yes=6 (40%) No=9 (60%)	Yes=8 (53.3%) No=7 (46.7%)	Yes=8 (61.5%) No=5 (38.5%)	Yes=16 (48.5%) No=17 (51.5%)
Self-Selected Gait Speed (m/s)	1.23 ± 0.15	1.25 ± 0.13	1.22 ± 0.11	1.21 ± 0.14	1.31 ± 0.26	1.18 ± 0.19
Stance Duration (s)	0.66±0.06	0.66±0.05	0.63±0.03	0.64±0.06	0.62±0.06	0.65±0.07 *
KOOS Pain	82.31 ± 6.77	93.24 ± 4.56 *	85.79 ± 5.21	93.86 ± 7.02 *	83.82 ± 9.38	90.10 ± 11.32
KOOS Symptoms	74.67 ± 11.48	90.18 ± 4.31 *	77.67 ± 14.31	91.42 ± 4.09 *	73.69 ± 12.59	92.46 ± 7.62 *
KOOS Activities of Daily Living	95.06 ± 4.16	98.47 ± 2.39 *	95.69 ± 3.50	99.31 ± 1.35 *	95.25 ± 6.66	99.20 ± 1.61 *
KOOS Sport and Recreation	65 ± 10.09	81.25 ± 12.53 *	75.42 ± 8.39	90.67 ± 8.21 *	73.46 ± 15.46	93.48 ± 7.65 *
KOOS Knee-Related Quality of Life	50.67 ± 13.43	71.88 ± 15.96 *	64.58 ± 12.87	80 ± 14.41 *	62.5 ± 14.21	86.36 ± 9.81 *

* Indicates statistically significant differences between Symptomatic and Asymptomatic Individuals within each post-ACLR cohort; PT: Patellar Tendon, H: Hamstring, A=Allograft, QT=Quadriceps Tendon