Received: 30 October 2020 | Revised: 13 March 2021 | Accepted: 26 April 2021

DOI: 10.1002/jor.25070

RESEARCH ARTICLE

Journal of Orthopaedic Research®

Individuals following anterior cruciate ligament reconstruction practice underloading strategies during daily activity

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Funding information
National Center Medical Rehabilitation Research, Grant/Award Number: K12 HD0055929; International Society of Biomechanics, Grant/Award Number: Matching Dissertation Grant; North American Society for the Psychology of Sport and Physical Activity, Grant/Award Number: Graduate Student Research Grant

Abstract

Underloading the surgical limb has been described in biomechanical studies across recovery time points following anterior cruciate ligament reconstruction (ACLr). This study aimed to examine the extent to which laboratory findings translate to daily activities. Limb loading was quantified during a sit-to-stand task in laboratory testing and throughout 2 days of daily activity in 15 individuals 114.8 (17.2) days post-ACLr and 15 controls. Vertical force impulse calculated from force platform (laboratory) and pressure insoles (daily) was used to quantify limb loading. Between-limb symmetry was calculated for limb loading and knee strength measures, 2 × 2 GLM repeated measures determined a significant group-by-limb interaction on daily limb loading. Surgical limb daily loading was lower compared to nonsurgical ($p < .001$; effect sizes [ES] = 0.63), and control matched limbs (surgical: $p = .037$, ES = 0.80 and nonsurgical: $p = .02$, ES = 0.89). No group differences were found in total daily loading (summed loading between limbs; $p = .18$; ES = 0.50) and time performing weight-bearing activities ($p = .32$; ES = 0.36). Pearson's correlation determined that between-limb symmetry in daily loading was related to sit-to-stand loading ($r = .62$; $p = .01$) and knee extensor strength symmetry ($r = .6$; $p = .02$) in the ACLr group. These data support the presence of underloading behaviors in individuals 10–14 weeks following ACLr that are consistent with previous biomechanical studies and current biomechanical data. Knee extensor weakness was related to greater underloading. Asymmetrical loading quantified in the laboratory is practiced throughout the day in individuals post-ACLr. Practice afforded by daily activities represents powerful contributors to learning of a pattern that contrasts the goal of rehabilitation exercises.

KEYWORDS

ACL, biomechanics, daily activities, learned nonuse, wearable sensors

1 | INTRODUCTION

Biomechanical studies have shown that individuals following anterior cruciate ligament reconstruction (ACLr) adopt loading strategies that shift the mechanical demands away from the surgical limb.[1,2] Underloading the surgical limb is likely an adaptation in response to early postoperative (2–4 weeks) joint level impairments, such as pain and swelling, decreased range of motion, and muscle weakness. However, these patterns persist up to 2.5 years post-ACLr and have been observed during submaximal tasks and after the resolution of joint impairments.[3–5] These patterns observed during landing tasks at 1 and 2 years postsurgery have been associated with increased risk for reinjury.[6,7] More recent investigations of limb and joint loadings suggest that underloading of the surgical knee in early recovery and rehabilitation may contribute to poor cartilage health, a precursor for the development of osteoarthritis.[8–10] As such, the persistence of underloading is considered mal-adaptive. The long-term persistence of underloading behaviors suggests that traditional rehabilitation protocols that focus on restoration of limb and joint loading do not adequately reverse this process.[11,12]

A recent biomechanical study suggests that nonuse or underuse may be a contributor to the persistence of underloading. Individuals 10–14 weeks following ACLr spontaneously underloaded the surgical limb during laboratory analyses of submaximal tasks, despite having the ability to meet the mechanical demands of these tasks.[2] The mismatch between what individuals are capable of doing and what they actually do naturally may be indicative of a pattern of "learned nonuse."[13,14] Learned nonuse is a phenomenon described in the neuroscience literature that refers to the situation in which stroke survivors do not use their hemiparetic arm when given a choice despite the fact that they have the ability to use it when the uninvolved arm is constrained. The increased effort, pain, or failure to complete tasks with the involved arm is thought to reduce spontaneous use, and this pattern is practiced and learned over time.[13,15,16] While laboratory comparisons between natural or spontaneous limb loading behavior and loading ability indicate nonuse or underuse with respect to limb loading,[2] the underuse characterized in a laboratory environment in a few bilateral tasks cannot represent spontaneous limb loading behaviors throughout the day.

If a pattern of underuse is present in individuals following ACLr, the loading practice afforded in daily activities, by virtue of its volume, can serve as powerful mechanisms for the development and maintenance of this mal-adaptive strategy. Our current understanding of underloading strategies in this population is limited to laboratory-based biomechanical assessments of force distribution between limbs during bilateral tasks. Given the variety of functional tasks performed throughout the day, it is not known if what is observed during these tasks is reflective of a general underuse loading behavior. It is conceivable that attention to movement quality during rehabilitation sessions does not carry over into daily activities with different time and attentional demands. Thus, it is important to understand how individuals load their limbs during activities of daily living.

Advancements in technology offer solutions to monitor limb loading outside of the laboratory through wearable plantar insoles that are robust enough to estimate vertical forces for a variety of movements over the span of an entire day.[17] A better understanding of how individuals load their limbs throughout the day is particularly important during early rehabilitation as it represents a critical time for reversing mal-adaptive loading behavior. Early rehabilitation is a time when joint level impairments are resolving, and individuals are generally increasing their daily activities while progressing through exercises with greater loading demands. Therefore, the primary aim of this study was to determine if limb loading throughout the day differs between individuals 3 months post-ACLr and healthy matched individuals. A secondary aim was to determine if limb loading symmetry observed in the laboratory is related to limb loading symmetry during daily activities. In addition, an exploratory analysis was conducted to determine the relationship between daily loading symmetry and patient-reported function, and clinical measures of strength. We hypothesized that when compared to healthy individuals, individuals following ACLr will underload the surgical limb during daily activities, and the limb loading symmetry observed in the laboratory will relate to limb loading symmetry during daily activities in individuals following ACLr. In addition, those following ACLr with poorer reported function and greater strength deficits will exhibit greater underloading in the laboratory and daily loading assessments.

2 | METHODS

2.1 | Participants

A priori sample size analysis on primary variables of interest (daily limb loading and daily limb loading symmetry) was performed based on pilot data of five individuals from each group (ACLr and Control). The largest minimum sample size of 10 participants per group was required to detect a difference of 0.13 in daily limb loading symmetry ratio with a power of a 0.80 and alpha level of .05.

Two groups of participants were recruited for this study: individuals 114.8 (17.2) days following ACLr (ACLr; $n = 15$) and healthy matched controls (CTRL; $n = 15$). These participants represented a subset of participants enrolled in a previously published study comparing the performance of bilateral tasks in the laboratory during natural, instructed, and feedback conditions.[2] Participants in the ACLr group were recruited from four physical therapy clinics in the greater Los Angeles area. They were enrolled in the study if they were (1) between the ages of 14 and 50, (2) 10–14 weeks status post-ACLr, and (3) did not have weight-bearing restriction following surgery, (4) currently participating in physical therapy, and (5) cleared to perform the experimental tasks. Participants in the control group were recruited to match the participants in the ACLr group based on age- (+/− 2 years), sex-, height-, weight-, and physical activity before surgery (Sports Activity and Function Form from the Cincinnati Knee Rating System). They were excluded if they reported: (1) prior or current ligamentous or meniscal injury or surgery on lower extremities, (2) current or history of pathology or morphology in lower extremities that could cause pain or discomfort during physical activity (contralateral limb; ACLr group), and (3) any pathology or medical condition that may impair their ability to perform the tasks proposed in this study. The researchers did not control for or record specific rehabilitation interventions. However, the treating physical therapists agreed that their treatments followed standard rehabilitation protocols that emphasized the early restoration of range of motion and progressive strength and functional exercises.

The present study was conducted at the University of Southern California, Division of Biokinesiology and Physical Therapy's Human Performance Laboratory. All procedures were explained to each participant, and informed consent was obtained as approved by the Institutional Review Board of the University of Southern California, Health Sciences Campus. Parental consent and youth assent were obtained for participants under the age of 18 years. After consenting, participants filled out the subjective portion of the International Knee Document Committee (IKDC) form to understand current knee function, symptoms and pain, and Sports Activity and Function Form from the Cincinnati Knee Rating System. These participants represent a subset of data published previously comparing the performance of bilateral tasks in laboratory conditions during natural, instructed, and feedback conditions. The current study adds to these data by assessing limb loading behaviors in a more ecological environment.

2.2 | Laboratory testing

Before laboratory testing, participants warmed up on a stationary bike for 5 min. Isometric knee extensor and flexor strength were tested (Humac2015 dynamometer, Computer Sports Medicine Inc.) while participants were seated with their knee and hip positioned at 60° and 90°, respectively. They performed 3 trials of 3-s maximum knee extensor and flexor isometric contractions. Torque data were sampled at 100 Hz, and peak torque from the best of three trials was used to represent knee extensor and flexor strength. Quadriceps and hamstrings strength symmetries were defined as a ratio of surgical/nonsurgical (matched limbs for CTRL group).

After the strength testing, participants performed sit-to-stand tasks using procedures that attempt to capture their natural loading behavior. Laboratory testing procedures are described in detail in a previous publication.[2] Briefly, participants were asked to sit on a stool with no armrests following the application of a lower extremity marker set. The height of the stool was positioned so that the participants' knees were flexed to 90° and each foot rested on a force platform separately. They were asked to stand up from the stool and stand still for 10 s as required for calibration of the camera system. In an effort to capture an individual's natural or spontaneous loading behavior, data were collected covertly and began before participants rose from a seated position and continued during standing. Emphasis was placed on standing still for the cameras, and no instructions regarding weight-bearing or limb loading were given to the participants. Four successful sit-to-stand trials were collected for analysis. A successful trial was determined if the L5S1 trajectory was present for the determination of the initiation and cessation of the sit-to-stand and both feet were placed within the force plates during the task.

Kinematic data were collected using a marker-based motion capture system (BTS Smart-DX; BTS Bioengineering Corp). Three-dimensional L5S1 marker-coordinates were reconstructed (SMART Tracker, version 1.10; BTS Bioengineering Corp) and low-pass filtered using fourth-order zero-lag Butterworth filter with a 6 Hz cutoff frequency (Visual 3D; C-motion, Inc.). The initiation of the sit-to-stand task was defined as the time at which the L5S1 marker displaced vertically greater than two *SD*s of average (from the previous 2 s) resting/sitting position. The termination of the task was defined as the subsequent peak L5S1 vertical position.

Ground reaction forces were collected using two force platforms (BTS P-6000, BTS Bioengineering Corp). Kinematic and ground reaction force data were collected synchronously using BTS Smart-capture software v2.8 (BTS Bioengineering Corp) sampled at 250 and 1000 Hz, respectively. Limb loading during the sit-to-stand task from the task initiation to termination was quantified with vertical GRF impulse. The impulse was calculated as the area under the body mass normalized vertical GRF time curve during the sit-to-stand task using a custom Matlab program (Mathworks). Data were averaged across four trials for analysis.

2.3 | Ecological testing

Following laboratory testing, participants received a pair of the wireless plantar pressure insoles corresponding to their shoe size. The instrumented insoles replaced the original insoles of participants' own athletic shoes. They were instructed to wear the insoles for 9 h a day, for two weekdays within a week after the laboratory testing. For testing, participants were asked to choose 2 days that represented typical weekday activities and did not include physical therapy. Participants wore the insoles within an hour of waking. To avoid potential confounding issues related to insole fitting, activation, and synchronization, the same investigator met with each participant to activate and calibrate the sensors before data collection on each testing day. Procedures were followed according to the manufacturer's instructions. Shoe insoles were calibrated to eliminate signals measured as a product of shoe/insole fit. Before insole calibration, the investigator placed the insoles in the shoes that the participants agreed to wear all day. Participants tightened the shoelaces and took a few steps around the room. For calibration, participants sat down and lifted both feet off the ground with the toes held in a relaxed position. At this time, the investigator zeroed the insoles so that the vertical force measure read zero. Participants wore the same pair of shoes for both data collection days.

Vertical forces were measured using the wireless sensor insoles (Moticon science). Each insole consists of 13 capacitive pressure sensors positioned across the heel, midfoot, forefoot, and toes.[17] Data sampled at 25 Hz were stored in the insoles and downloaded after data collection to a password-protected personal computer for analysis.

While the concurrent validity of individual limb loading between the insoles has been determined to be acceptable,[17] concurrent validity for measures of limb loading symmetry has not been established. A pilot study was conducted to establish the concurrent validity for measures of limb loading and limb loading symmetry between the wearable insoles and force platforms during daily functional tasks. For this study, participants donned the insoles as described above and performed a series of continuous functional tasks, including sit-to-stand, walking, stooping, and turning tasks over a series of eight force platforms (BTS P-6000; BTS Bioengineering Corp). The vertical force impulse of each limb was calculated from the force platforms and output from the wireless insoles using the procedures described in detail below. Limb loading was calculated as the vertical force impulse from each instrument for each limb. Limb loading symmetry was calculated as a ratio of nondominant/dominant limb vertical force impulse. Strong agreement between measurement systems for limb loading and limb loading symmetry was determined with significant intra-class correlation coefficients (ICC: 0.93–0.97). Refer to the supplementary table for specific ICC and minimal detectable change of each measure.

For the insoles, raw force data were calculated as the product of sensor pressure (N/cm^2) and sensor area (cm^2), summed across 13 sensors, and exported by the manufacturer as total vertical force. Vertical force (N) was normalized to an individual's body mass (Kg). Daily limb loading was calculated from vertical force during weight-bearing activities. Weight-bearing activities were defined using vertical force data summed between limbs/insoles. Based on pilot testing, vertical force less than 25% body weight for individual limbs was determined to largely represent nonweight-bearing activities. Therefore, weight-bearing was considered any time in which the summed between-limb vertical force was greater than 50% body mass. To avoid eliminating data below this threshold that occurred during transitions between weight-bearing and nonweight-bearing, data were included if the time during which summed vertical force was below 50% and followed or preceded by the force that exceeded 50% for at least 1 s. Vertical force impulse (N*s/Kg) was calculated as the area under the normalized vertical force (N/Kg) time curve during weight-bearing activities across 8 h for each limb to represent daily limb loading. The 8-h period began 30 min after monitoring started. To characterize overall weight-bearing activities across participants, total daily limb loading was calculated by summing daily weight-bearing limb loading from both limbs, and the amount of time performing weight-bearing activities was also calculated. Data for all daily loading variables were averaged across two data collection days. For all analyses, limbs in the control group were matched based on limb dominance regardless of surgery.

2.4 | Between-limb loading symmetry

Limb loading symmetry was calculated during sit-to-stand (LLS_{sst}) performed in the laboratory and during daily activities (LLS_{day}), as between-limb ratios of vertical GRF impulse and vertical force impulse calculated as a ratio of surgical/nonsurgical (matched limb for CTRL group). LLS of 1 indicates the equal distribution of weight between the limbs, LLS less than 1 indicates loading of the surgical/matched limb was less than the nonsurgical/matched limb, and LLS greater than 1 indicates loading of the surgical/matched limb is greater than the nonsurgical/matched limb.

2.5 | Statistical analysis

2 (Group) × 2 (Limb) General Linear Model repeated measures analysis was performed to assess the effects of group and limb on daily limb loading. In the case of a significant interaction, independent and paired *t* tests were conducted for post hoc analyses. Independent-samples *t* tests were performed to compare the difference in total daily limb loading and amount of time performing weight-bearing activities between the ACLr and CTRL groups. Furthermore, to determine the magnitude of the effect, Cohen's *d* effect sizes (ES) were calculated and interpreted as small (0.2), medium (0.5), or large effects (0.8). Pearson's product-moment correlation was used to determine the relationships between limb loading symmetry during sit-to-stand (LLS_{sst}: laboratory testing) and limb loading symmetry during daily loading (LLS_{day}: ecological testing) for the ACLr group. Pearson product-moment correlation was used to determine the relationship between LLS_{day}, IKDC scores, and knee extensor and flexor strength ratios. The significance level for all the tests was set at $\alpha = .05$ (IBM SPSS Statistics, Version 22, IBM Corp).

3 | RESULTS

Participants' descriptive information is reported in Table 1.

A main effect of limb (Wilks $\lambda = 0.37$; $F = 47.68$; $p < .001$; Partial Eta Squared: 0.63) and an interaction effect of limb and group (Wilks $\lambda = 0.48$; $F = 30.56$; $p < .001$; Partial Eta Squared: 0.52) were noted (Table 2) for daily limb loading. In the ACLr group, on average, daily limb loading in the surgical limb was significantly lower than the nonsurgical limb (22%, $p < .001$; ES = 0.63). For the CTRL group, no difference in daily limb loading was observed between limbs ($p = .33$; ES = 0.07). When considering between groups, the surgical limb in the ACLr group exhibited significantly lower daily limb loading compared to both the surgical matched (24%, $p = .04$; ES = 0.80) and nonsurgical matched limbs (26%, $p = .02$; ES = 0.89) in the CTRL group. No differences were observed between the nonsurgical limb in the ACLr group and the surgical matched ($p = .72$; ES = 0.13) and the nonsurgical matched ($p = .58$; ES = 0.20) limbs in the CTRL group.

No difference in the total daily limb loading was found between groups ($p = .18$; Table 3; ES = 0.50). No difference in the amount of time performing weight-bearing activities was found between groups ($p = .32$; ES = 0.36).

When considering knee extensor strength ratios for participants in the ACLr group data ranged 0.10–1.62. Data from one subject (1.62) was considered an outlier as it fell 1.5 times the interquartile range above the 3rd quartile. Knee extensor strength ratio from this subject was removed from further analyses. Average knee extensor strength ratio was 0.52 (0.28) (range: 0.10–0.98) and knee flexor strength ratio was 0.74 (0.13) (range: 0.52–0.97). IKDC scores ranged from 37.93 to 79.31 (average: 58.8 [10.9]).

Daily limb loading symmetry (LLS_{day}) was correlated with limb loading symmetry during sit-to-stand (LLS_{sst}) in the ACLr group ($r = .62$; $p = .01$; Figure 1). $LLS_{day,}$ was correlated with knee extensor strength symmetry ($r = .6$; $p = .02$; Figure 2). No significant correlations were found between $LLS_{day,}$ and IKDC scores ($r = .25$; $p = .4$) or knee flexor strength symmetry ($r = .32$; $p = .25$).

TABLE 1 Participants' characteristics

	ACLr (*n* = 15)	CTRL (*n* = 15)
Age (years)	26.3 (10.8)	26.1 (10.7)
Sex	6M/9F	6M/9F
Height (cm)	1.71 (0.08)	1.71 (0.08)
Weight (kg)	71.3 (10.3)	72.2 (1.01)
Days post-ACLr	114.8 (17.2)	–
Graft type (*n*)		
Bone-patellar tendon-bone autograft	8	–
Hamstring autograft	1	–
Quad autograft	1	
Allograft	5	–
Sports activity and function	95.7 (25.5)	96.7 (11.6)
IKDC overall	58.8 (10.9)	99.5 (1.2)

Note: Values presented as mean (*SD*s) unless otherwise indicated.
Abbreviation: ACLr, anterior cruciate ligament reconstruction.

4 | DISCUSSION

The presence and persistence of underloading in surgical limb and knee during a variety of tasks following ACLr are well supported by data collected in biomechanics laboratories; however, it is not known how these findings relate to real-world loading behaviors. The overall aim of this study was to determine the extent to which individuals 3 months post-ACLr spontaneously underload their surgical limb throughout the day and to see how these behaviors compared to those measured in a laboratory setting. By quantifying loading in an ecological environment, the present study establishes the extent to which underloading is practiced throughout the day. Previous work suggests that underloading behaviors may be due to learned nonuse strategies versus the inability to meet the demands of loading. To provide some insight into the influence of functional capacity and current functional status daily loading, we examined how thigh strength and patient-reported function related to daily loading.

TABLE 3 Comparisons of total daily limb loading, total daily limb loading time between groups

	ACLr	Control
Total daily limb loading magnitude (N*s/kg)	88,865.93 (32,189.44)	104,696.05 (30,676.95)
Total daily limb loading time (min)	156.89 (47.54)	173.97 (45.57)

Note: *No significant difference noted between groups. Values presented as mean (*SD*).
Abbreviation: ACLr, anterior cruciate ligament reconstruction.

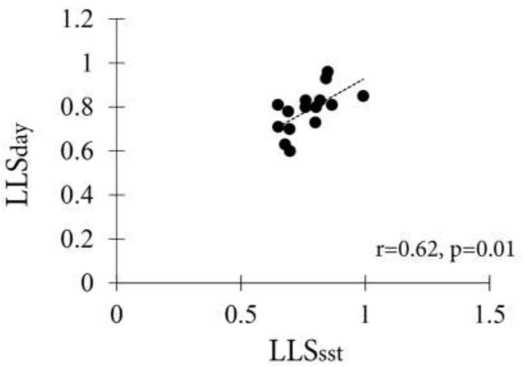

FIGURE 1 This figure illustrates the relationship between the limb loading symmetry during sit-to-stand in the laboratory (LLS_{sst}) and the daily limb loading symmetry in the ecological environment (LLS_{day}) in ACLr group. ACLr, anterior cruciate ligament reconstruction

Daily limb loading data indicate that individuals 10–14 weeks post-ACLr underloaded their surgical limb throughout the day. When considering weight-bearing activities across two weekdays, loading in the surgical limb was 22%–26% lower when compared to the nonsurgical limb and both control limbs, while no difference was observed between limbs in the control group. This is reflected in 22% between-limb loading asymmetry (LLS = 0.78) in the ACLr group compared to a 3% asymmetry (LLS = 0.97) in the healthy control group. Inspection of individual LLS data suggests that there was a range of deficits across participants in the ACLr group (Figure 3). If

TABLE 2 Comparisons of daily limb loading between groups and limbs

	ACLr		CTRL	
	Surgical	Nonsurgical	Surgical matched	Nonsurgical matched
Daily limb loading (N*s/kg)	39,275.90 (15,534.36)*	49,590.03 (16,966.86)	51,776.82 (15,722.76)	52,919.23 (15,259.99)

Note: ACLr surgical versus ACLr nonsurgical ($p < .001$; ES = 0.63).
CTRL surgical matched versus CTRL nonsurgical matched ($p = .33$; ES = 0.07).
ACLr surgical versus CTRL surgical matched ($p = .04$; ES = 0.80).
ACLr surgical versus CTRL nonsurgical matched ($p = .02$; ES = 0.89).
ACLr nonsurgical versus CTRL nonsurgical matched ($p = .58$; ES = 0.20).
ACLr nonsurgical versus CTRL surgical matched ($p = .72$; ES = 0.13).
Abbreviations: ACLr, anterior cruciate ligament reconstruction; ES, effect sizes.

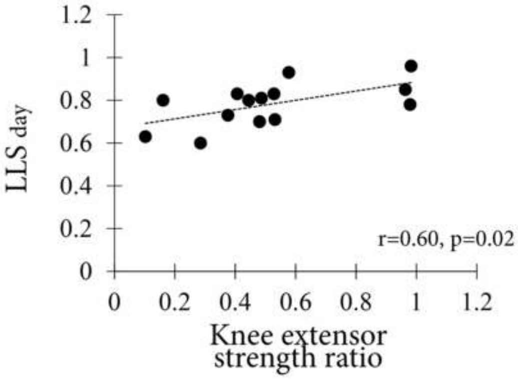

FIGURE 2 This figure illustrates the relationship between knee extensor strength ratio and daily limb loading symmetry (LLS_{day}) in ACLr group

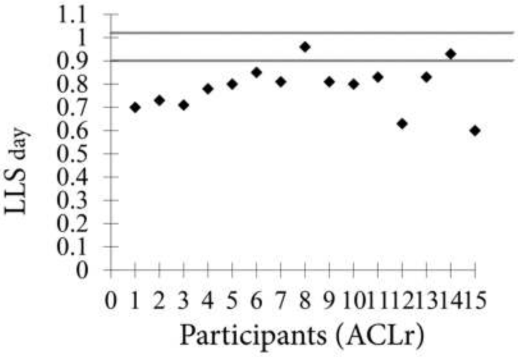

FIGURE 3 This figure illustrates individual daily limb loading symmetry in the ACLr group. The dashed lines indicate the range of typical daily limb loading symmetry in healthy controls. ACLr, anterior cruciate ligament reconstruction

we are to consider the mean and *SD* of symmetry observed in the healthy controls as a range of typical symmetry (0.96 ± 0.06; Figure 3, dashed lines), we see that only two of the 15 individuals post-ACLr fell within that range. However, 11 individuals exhibited asymmetries between 10% and 30%, and two others had loading deficits greater than 30%. The majority of participants in the ACLr group demonstrated some degree of underloading during daily activities. The existence of this behavior in real-world activities strengthens the argument that individuals 10–14 weeks post-ACLr do not spontaneously load their surgical limb to the same degree as they load their nonsurgical limb across daily activities.

Total time performing weight-bearing activities and total limb loading (sum of loading between limbs) provide some insight into the extent to which these behaviors were practiced. Differences between groups for time and loading were not significant, suggesting that loading behavior was similar across groups. It may be expected that individuals 10–14 weeks post-ACLr would decrease overall weight-bearing time and magnitude compared to healthy individuals because they are just returning to daily activities. In addition, these data contrast previous work by Bell et al.,[18] who found that individuals 6–67 months post-ACLr spend less time engaged in moderate intensity physical activity and have a lower step count compared to healthy controls. The similarities noted between groups in the current study could be attributed to the fact that loading was monitored across only 2 days that were considered typical weekdays. It is not known how these data reflect behaviors across the week. Further work is needed to fully understand loading and activity behaviors across rehabilitation and recovery.

While data from the present study represent only a snapshot of daily loading, they highlight the potential effect daily activities have on reinforcement and learning of underloading behaviors. Repetition of practice during daily activities across a variety of tasks and in different contexts is a powerful mechanism for the development and maintenance of a new motor skill or behavior.[19] When considering the amount of time per day one might dedicate to rehabilitation exercises, the 157 min (more than 2.5 h) of daily loading practice observed in the ACLr group far exceeds the time dedicated to specific loading exercises. The volume of practice afforded in daily activities can serve to reinforce these underuse loading patterns. This is particularly important at 10–14 weeks following ACLr when individuals are not only progressing to more challenging exercises with greater loading demands in their rehabilitation, but they are also re-establishing typical movement patterns. If present, learned underuse may explain, in part, the persistence of underloading strategies up to 2.5 years post-ACLr across submaximal tasks and after the resolution of joint impairments.[3,11]

The positive relationship between LLS_{day} and LLS_{sst} measured in the laboratory provides support for the presence of underuse. The strength of this relationship is somewhat surprising given that daily loading measures consisted of both double and single limb activities, including gait. However, it suggests that underloading behavior during a single functional sit-to-stand task may be generalized to the variety of tasks performed throughout the day. Our recent work provides evidence of this underuse phenomenon by experimentally determining that individuals' natural loading patterns do not match their loading abilities during submaximal double limb tasks.[2] The present study indicates that the underloading quantified in the laboratory reflects a pattern of underloading in daily activities; however, it cannot wholly support the presence of underuse. Data captured throughout the day represent a variety of activities, some of which may exceed an individual's current loading ability. The current data did not allow for differentiation of the type of tasks performed, but it is assumed that individuals performed tasks with greater demands than a sit-to-stand. For these participants, self-reported IKDC scores, similar to those previously reported,[16,20,21] indicate that on average individuals in the ACLr group were progressing typically. We do not know to what extent the activities performed exceeded the individuals' loading abilities; therefore, we cannot determine the degree to which underuse contributes to underloading in these data. One may assume that underloading, not attributed to underuse, would be accentuated if participants performed activities that exceed their current abilities.

Some insight into potential loading abilities comes from assessments of strength. We found that knee extensor strength ratios were positively correlated with LLS_{day}. This is not surprising as knee extensor strength deficits related to lower LLS_{day} as they are common following ACLr and are attributed to decreased function in early recovery.[22] Knee extensor strength ratios were on average 0.52 (0.3), indicating an average of a 48% deficit in the surgical limb across participants. These deficits are larger than deficits previously reported at 3–4 months post-ACLr (28%–38%)[23,24] and do not meet clinical strength recommendations.[12] As such, this study sample may represent those who have lower loading abilities. Interestingly, two of the three individuals who exhibited symmetrical strength (within 5% of the nonsurgical limb) underloaded their surgical limbs during the day 15% and 22%. Together these data illustrate a complex interaction between physical metrics of ability and behavior. Further work, including a more detailed assessment of behaviors and in a larger sample of participants with a wider range of muscle strength deficits, is needed to understand the distinct influences of underuse and strength on loading behavior.

A strong positive correlation between the LLS_{day} and LLS_{sst} has potential implications for the identification of underloading strategies in clinical practice. Measures of vertical force underfoot in the clinic may help identify underloading behavior at 3 months post-ACLr. Assessment of loading behavior in the clinic may be complicated if patients are aware that they are being assessed. Efforts were made to assess natural loading behavior during sit-to-stand by distracting attention from the task being assessed and focusing it on the subsequent task. In this case, instructions to the participants focused on standing still for camera calibration procedures. They were not told that data were being collected as they stood up for these procedures. Future work should be conducted to determine the feasibility of assessing more natural loading in a clinical setting.

When taken together, these findings have implications for the restoration of limb loading in post-ACLr rehabilitation. The present study suggests that it is imperative to shape loading behavior throughout the day. Identification of mechanisms that encourage more symmetrical loading throughout the day as a means of increasing loading of the surgical limb may be warranted. Recent work exploring improvements in knee joint loading during gait suggests that increasing loading forces can improve knee loading specific variables. However, this intervention used specific instruction and ground reaction force feedback during a limited intervention period.[25] Care should be taken when applying the findings of this study to interventions throughout the day. Moreover, adequate quadriceps strength may be necessary to accommodate loads in the surgical limb throughout the day, and restoration of strength must remain an important goal in early recovery. While it may be reasonable to assume sagittal plane knee loading is also reduced in the surgical limb, this was not measured. It is not known how instructions to increase limb loading will affect knee joint loading without feedback and in uncontrolled environments. Further work is needed to determine effective means of intervening throughout the day.

The limitations of this study provide a framework for future work. Given the population studied and the relatively small sample size, these data cannot be generalized to all individuals 10–14 weeks post-ACLr or to those at other time points in recovery. While this study describes a general pattern of underloading during daily activities, quantification of loading was restricted to overall loading, and the specific types of loading practice cannot be characterized with these data. This study provides support for underuse; however, understanding how the demands of the specific activities individuals chose to participate match with their ability to meet those demands is needed to fully understand if nonuse is a factor. Further information regarding daily activities along with loading profiles is needed to understand the types of activities that contributed to these daily loading data. Characterization of loading practice over more than 2 days, including days in which individuals would be expected to participate in recreational activities, is needed. Last, the participants wore the insoles after the laboratory visit, which may influence their natural loading behavior as attention to loading symmetry might be encouraged. If the loading symmetry is encouraged after the laboratory visit, the underloading strategy observed during daily activities might be underestimated.

5 | CONCLUSIONS

While the interpretation of these data may be limited, this is the first study to characterize underloading in daily activities in individuals following ACLr. It establishes the presence of spontaneous underloading behaviors in the surgical limb of individuals 10–14 weeks following ACLr. These deficits are consistent with what is reported across biomechanical studies and is supported with biomechanical data in the current study. Addressing daily underloading behaviors is critical given that the amount and quality of practice afforded by daily activities represent powerful contributors to the learning of a pattern that contrasts the goal of rehabilitation exercises.

ACKNOWLEDGMENTS

This research was supported in part by grant K12 HD0055929 from the National Center Medical Rehabilitation Research (NICHD). Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the NIH. This research was also partially supported by the Matching Dissertation Grant from the International Society of Biomechanics and Graduate Student Research Grant from North American Society for the Psychology of Sport and Physical Activity. The authors would like to acknowledge Competitive Athletes Training Zone Physical Therapy for the support and assistance with this study.

AUTHOR CONTRIBUTIONS

Ming-Sheng Chan: contributed to research design, data acquisition, analysis and interpretation of data, and drafting the paper. **Susan M. Sigward**: contributed to research design, interpretation of data, and revising of the paper. All authors have read and approved the final submitted manuscript.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

How to cite this article: Chan M-S, Sigward SM. Individuals following anterior cruciate ligament reconstruction practice underloading strategies during daily activity. *J Orthop Res*. 2022;40:565-572. https://doi.org/10.1002/jor.25070