Accepted Manuscript (Uncorrected Proof)

Title: The Interactive Effect of Foot Orthoses on Time to Peak of Ground Reaction Force Components and Center of Pressure in Individuals with Anterior Cruciate Ligament Reconstruction and Pronated Feet at 6, 12, and 18-month Post-Surgery During Running

Authors: Ebrahim Piri[1,2], AmirAli Jafarnejadgro[1,*], Mahrokh Dehghani[1], Afsaneh Enteshari-Moghaddam[3]

1. *Department of Sports Biomechanics, Faculty of Educational Sciences and Psychology, University of Mohaghegh Ardabili, Ardabil, Iran.*
2. *Department of Molecular Medicine and Surgery, Karolinska Institutet, Solna, Sweden.*
3. *Department of Internal Medicine, Faculty of Medicine, Ardabil University of Medical Sciences, Ardabil, Iran, Iran.*

To appear in: ***Physical Treatments***

Received date: 2025/11/10

Revised date: 2026/02/09

Accepted date: 2026/06/07

First Online Published: 2026/06/23

Please cite this article as:

Piri E, Jafarnejadgro AA, Dehghani M, Enteshari-Moghaddam A. The Interactive Effect of Foot Orthoses on Time to Peak of Ground Reaction Force Components and Center of Pressure in Individuals with Anterior Cruciate Ligament Reconstruction and Pronated Feet at 6, 12, and 18-month Post-Surgery During Running. ***Physical Treatments.*** Forthcoming 2026. DOI: http://dx.doi.org/10.32598/ptj.2026.348.24

DOI: http://dx.doi.org/10.32598/ptj.2026.348.24

Abstract

Purpose: This study investigated the interactive effects of different foot orthoses (FOs) and post-operative duration on the time to peak (TTP) of ground reaction force (GRF) components and center of pressure (COP) excursions in individuals with anterior cruciate ligament reconstruction (ACLR) and pronated feet (PF).

Methods: In a single-blinded (assessor-blinded), controlled study, 45 right-limb dominant males with ACLR and PF were stratified into three groups based on post-operative time: 6, 12, and 18-month. A control group of 15 healthy individuals with neutral feet was also included. Participants ran at 3.2 m/s under four-foot conditions: control shoe, placebo orthotic, arch-support orthotic, and double-density orthotic. GRF and COP data were collected using a force platform. A 4×4 mixed-model ANOVA was used to analyze main and interaction effects on TTP and COP variables.

Results: Significant main effects of group were found for all TTP variables and COP excursions ($p < 0.05$), indicating distinct loading patterns across recovery stages. The 6-month ACLR group demonstrated a significantly lower TTP for lateral force and greater TTP for medial, anterior, posterior, and active vertical peaks compared to healthy controls. Significant main effects of FOs were observed for TTP Peak medial, posterior, anterior, and COP excursions ($p < 0.05$). Crucially, significant group × FOs interactions were detected for TTP Peak medial, anterior, active vertical peak, and COP excursions ($p < 0.05$).

Conclusion: The efficacy of foot orthoses following ACLR is recovery-phase dependent. Arch-support orthoses are particularly beneficial for modifying sagittal plane loading patterns during early rehabilitation at 6-month, whereas double-density orthoses provide superior frontal plane control during advanced stages at 12-month. These findings underscore the importance of phase-specific orthotic prescription following ACL reconstruction and highlight the need for individualized biomechanical assessment to optimize rehabilitation outcomes, improve dynamic loading control during running, and potentially reduce the risk of graft overload and long-term joint degeneration.

Keywords: Anterior Cruciate Ligament Reconstruction, Time to Peak, Ground Reaction Force, Center of Pressure, Running, Foot Orthoses.

Highlights

1) FOs effectiveness following ACLR varies across recovery stages (6, 12, and 18-month).
2) Arch-support orthoses show stronger effects on modulating sagittal plane forces at 6-month post-surgery.
3) Double-density orthoses exhibit greater influence on frontal plane motion control at 12-month post-surgery.
4) Recovery-phase-specific orthotic prescription may enhance biomechanical outcomes throughout rehabilitation.

Plain Language Summary

This study demonstrates that the biomechanical effects of custom FOs differ according to the time elapsed since ACLR surgery. For individuals with PF:

1) At 6-month after surgery, rigid arch-support orthoses showed stronger benefits in stabilizing forward and backward movement.
2) At 12-month after surgery, double-density orthoses appeared more beneficial in controlling side-to-side motion.
3) These findings suggest that FOs selection should be tailored to the patient's stage of recovery.

Introduction

Running is a high-impact activity that generates significant biomechanical loads on the lower extremities. The stance phase of running is characterized by rapid and forceful interactions between the foot and the ground, quantified by ground reaction forces (GRFs). While the peak magnitudes of these forces are critical, the temporal characteristics of their application and the spatial distribution of the resulting pressure are equally vital, yet often under-investigated, biomarkers of neuromuscular control and joint loading (1, 2).

Anterior Cruciate Ligament Reconstruction (ACLR) is the standard surgical intervention for restoring knee stability. However, it does not guarantee a return to pre-injury biomechanical function. A substantial proportion of individuals fail to return to their pre-injury activity levels, with re-injury rates remaining alarmingly high (3). Crucially, aberrant movement patterns often persist long after surgery, contributing to the development of post-traumatic osteoarthritis (PTOA) in over 50% of patients within 10-15 years (4). These persistent deficits are not solely a consequence of the knee injury itself but are often exacerbated by underlying biomechanical predispositions. Among these, a pronated feet (PF), posture is highly prevalent and influential. Excessive foot pronation, characterized by rearfoot eversion and tibial internal rotation, alters the entire lower extremity kinetic chain, increasing knee valgus moments and anterior tibial shear, thereby placing excessive rotational and translational stress on the healing ACL graft (5). The restoration of normal biomechanics post-ACLR is a prolonged process. During the critical return-to-sport phase and beyond, individuals often adopt compensatory gait strategies, such as a "stiff-legged" running, to protect the involved limb (6). These compensations are typically reflected not just in the amount of force but in the timing of its application and the location of its center.

The Time to Peak (TTP) of GRF components the duration from initial contact to the peak force in the vertical, anteroposterior, and mediolateral directions provides a sophisticated measure of loading rate and neuromuscular control. A shorter TTP indicates a more abrupt, high-impact loading pattern, which has been strongly linked to a higher risk of bone and cartilage stress injuries, and is commonly observed in ACLR populations (7, 8). For instance, a reduced TTP for the vertical impact peak signifies a sharper, less controlled deceleration of the body, transmitting higher-frequency shock waves through the lower limb. In the anteroposterior direction, a shorter TTP for the braking force implies a more rapid deceleration, increasing the anterior shear force on the tibia and, consequently, the strain on the ACL graft (9). Monitoring TTP across different phases of rehabilitation (e.g., 6, 12, and 18-month) can reveal whether patients are progressing towards more gradual and controlled force absorption or persisting with maladaptive, protective strategies.

The Center of Pressure (COP) is the point of application of the resultant GRF vector on the foot's plantar surface. Its trajectory in the mediolateral (COP-X) and anteroposterior (COP-Y) directions during the stance phase is a direct indicator of dynamic postural control and foot function (10). In individuals with pes planus, the COP pathway is often altered, typically exhibiting a more medial and prolonged excursion due to the collapse of the medial longitudinal arch (11). This altered pathway can destabilize the lower limb and increase knee valgus moments. For the ACLR population, impaired proprioception and neuromuscular control can further disrupt the normal COP path, reflecting an inability to efficiently manage the transfer of body weight during dynamic tasks (12). A more erratic or medially shifted COP can indicate poor stability and increased reliance on passive structures for support, potentially heightening the risk of re-injury. Therefore, quantifying COP excursion provides a window into the sensorimotor deficits that persist after ACLR and how they interact with a PF structure. While foot orthoses (FOs) are a common intervention to control foot kinematics and modulate GRF magnitudes, their longitudinal effects on the temporal (TTP) and spatial (COP) parameters of loading in this specific, at-risk population remain largely unexplored. Most research has focused on peak force values, overlooking the nuanced information contained in the rate of force development and plantar pressure distribution. However, emerging evidence suggests that kinetic timing and COP trajectory are sensitive to footwear and orthotic interventions. For instance, studies have shown that different footwear conditions can significantly alter the time to peak vertical GRF and braking forces. Furthermore, orthotic devices have been demonstrated to modify the COP path during gait in individuals with pes planus. Therefore, building on the established role of FOs in modifying foot kinematics and load distribution, we hypothesize that their therapeutic action in individuals with ACLR and PF will be directly measurable through changes in TTP of GRF components and COP excursions. These metrics are posited to provide a more integrated measure of dynamic loading patterns than peak forces alone.

Therefore, the primary objective of this longitudinal study was to examine the interactive effects of different foot orthoses (double-density, arch support, placebo) on the TTP of major GRF components and COP excursions during running in individuals with concurrent ACLR-PF, at three critical post-operative milestones: 6, 12, and 18-month. We hypothesized that both active orthoses would significantly increase TTP across various force components (indicating a more gradual load application) and normalize COP pathways (reducing excessive medial shift) compared to control and placebo conditions. Furthermore, we anticipated that these beneficial effects would be more pronounced at 12 and 18-month post-surgery, reflecting an enhanced neuromuscular adaptation to the orthotic intervention over the course of rehabilitation.

Methods

Study Population and Group Allocation

This investigation employed a single-blinded (assessor-blinded), controlled design with a total of 60 right-limb-dominant male volunteers. The primary cohort consisted of 45 participants presenting with both a PF type and a history of unilateral ACLR in the right leg. This group was stratified based on postoperative recovery time into three distinct intervals: short-term (6 ± 1-month), mid-term (12 ± 1-month), and long-term (18 ± 1-month). For comparative baseline analysis, a control group of 15 healthy individuals with neutral foot posture was also included. While participants could discern physical differences between the orthotic devices, all insoles were presented in identical, neutral packaging with standardized instructions to minimize expectation bias. A research assistant, who was not blinded to the condition, administered the randomized devices. Crucially, the assessor responsible for processing all kinetic and COP data was fully blinded to both participant group allocation and the foot condition being analyzed.

Inclusion criteria for the ACLR-PF group were rigorously defined. The order of the four foot conditions (control shoe, placebo orthotic, arch-support orthotic, and double-density orthotic) was randomized for each participant to control for order and fatigue effects. Pronation was objectively confirmed by a certified podiatrist through multiple metrics: a Foot Posture Index (FPI) score between 6 and 10, a navicular drop test result greater than 10 mm (13, 14), and a rearfoot eversion angle exceeding 4 degrees (15-17). A power analysis was conducted a priori using G*Power software (v3.1.9.2) for a repeated-measures ANOVA (within-between interaction). Based on comparable biomechanical literature examining orthotic interventions, a large effect size ($f = 0.4$, equivalent to $\eta^2 p \approx 0.14$) was specified. With an α of 0.05, power ($1-\beta$) of 0.80, 4 groups, 4 measurements, a conservative correlation among repeats of 0.5, and nonsphericity correction $\varepsilon = 1$, the analysis indicated a minimum total sample size of 36. Our final sample of 60 participants therefore provided adequate statistical power. All surgical interventions were performed using the

Anteromedial Portal technique to ensure independent and anatomic femoral tunnel placement, a critical consideration given the potential for altered tibial kinematics in PF. Post-operative imaging verified appropriate tunnel positioning, with no significant differences observed between patient groups ($p > 0.05$). The study received full ethical approval from the University of Mohaghegh Ardabili (IR.UMA.REC.1404.019) and was registered prospectively (IRCT20220129053865N2). All participants provided written informed consent. Table 1 summarizes the demographic, anthropometric, and clinical characteristics of all participants. No significant between-group differences were noted for age, height, weight, or BMI ($p > 0.05$). As expected, the healthy control group exhibited significantly lower Navicular Drop and FPI scores ($p < 0.001$).

Table 1. Participant Demographic and Clinical Characteristics

Characteristics	**Group A**	**Group B**	**Group C**	**Group D**	**p-value**
Age (years)	24.6 ± 0.8	26.1 ± 0.4	27.1 ± 0.1	25.3 ± 0.4	.082
Height (cm)	180.4 ± 3.2	179.2 ± 5.7	181.1 ± 2.1	178.1 ± 6.1	.912
Weight (kg)	80.4 ± 7.4	81.5 ± 5.2	80.6 ± 4.3	79.2 ± 6.5	.360
Body Mass Index (kg/m^2)	23.77 ± 0.64	24.01 ± 0.13	23.79 ± 0.82	23.10 ± 3.8	.547
Time Post-ACLR Surgery (months)	5.2 ± 0.8	9.1 ± 1.8	18.5 ± 4.2	-	**< .001**
Time Post-ACL Injury (months)	8.4 ± 1.2	12.3 ± 2.1	22.7 ± 5.3	-	**< .001**
Tegner Activity Score	5.2 ± 0.5	5.8 ± 0.7	6.5 ± 0.9	6.1 ± 0.6	0.563
Weekly Walking/Running (km)	12.3 ± 3.5	13.6 ± 4.2	13.1 ± 5.8	13.4 ± 6.2	0.845
Navicular Drop (mm)	12.7 ± 1.9	13.8 ± 1.1	12.9 ± 1.3	7.2 ± 1.8	**< .001**
Foot Posture Index	7.2 ± 0.2	8.3 ± 0.5	6.7 ± 1.7	3.2 ± 0.5	**< .001**
Graft Type *(Autograft/Allograft)*	Hamstring Autograft: n=15	Hamstring Autograft: n=15	Hamstring Autograft: n=15	Healthy	-

Group Designations: A: ACLR + PF (6-month post-surgery), **B:** ACLR + PF (12-month post-surgery), **C:** ACLR + PF (18-month post-surgery), **D:** Healthy Control Group. **Note:** Data are presented as Mean ± Standard Deviation. p-values in bold indicate statistical significance ($p < .05$).

Characteristics of the Different Foot Orthotics

Double-Density Orthotic: A custom-fitted device manufactured from ethylene-vinyl acetate (EVA), featuring a dual-durometer design. The medial aspect was constructed from a firmer material (Shore 60) to provide motion control, while the lateral aspect was softer (Shore 30) for cushioning. It incorporated a 12 mm medial longitudinal arch reinforcement (Fig. 1, A) (18).

Control Shoe: A standardized, neutral running shoe (adidas Runfalcon 5) with its stock, flat insole removed, establishing a baseline footwear condition.

Placebo Orthotic: A flat, single-layer foam insole with no corrective contours or posting, serving to control for the non-specific effects of simply wearing an insole.

Arch Support Orthotic: A rigid, contoured polyurethane device providing full-length arch coverage. Its design featured a 25 mm peak arch height and a 15 mm medial post, intended to significantly restrict midfoot mobility and rearfoot eversion (Fig. 1, B).

(A) **(B)**

Figure 1. (A) Double-density design illustrating the stiffer medial wedge (Shore 60) and raised arch profile. **(B)** Arch support orthosis highlighting the pronounced medial longitudinal arch contour and rigid structure.

Biomechanical Data Acquisition and Processing

Running biomechanics were assessed in a climate-controlled laboratory. Following a standardized warm-up and familiarization period, participants ran at a controlled velocity of 3.2 m/s (±5%) along an 18-meter runway. Kinetics were captured using a force platform (Bertec, USA) sampling at 1000 Hz (19). Five successful trials were recorded for each foot condition. Ground reaction force (GRF) data were processed using a validated pipeline. Raw signals were low-pass filtered (4th-order Butterworth, 20 Hz cutoff). The stance phase was identified using a 10 N force threshold. From the processed data, the following dependent variables were extracted for analysis: TTP for each GRF component, defined as the duration from initial contact to the respective force maximum (18). The trajectory of the point of application of the GRF vector, analyzed for total excursion in the mediolateral (COP-X) and anteroposterior (COP-Y) directions. All variables were averaged across the five trials for each participant and condition.

Statistical analyses

The normality of the data distribution was confirmed with the Shapiro-Wilk test. A 4 (Group) x 4 (Foot Condition) mixed-model Analysis of Variance (ANOVA) was employed to identify main effects and interaction effects on all biomechanical outcome measures. In the presence of a significant F-statistic, post-hoc pairwise comparisons were conducted with Bonferroni adjustment to control for Type I error. Effect sizes for significant findings were reported as partial eta squared (ηp^2), interpreted as small (≥0.01), medium (≥0.06), or large (≥0.14) (20). The threshold for statistical significance was established a priori at $p < 0.05$. All computations were performed using IBM SPSS Statistics, Version 26.

3. Results

3.1. TTP and COP

Significant main group effects were found for TTP Peak lateral (p<0.001; η^2=0.326), TTP Peak medial (p=0.006; η^2=0.199), TTP Peak posterior (p<0.001; η^2=0.299), TTP Peak anterior (p=0.005; η^2=0.203), TTP Active vertical peak (p=0.001; η^2=0.255), COP X (p=0.027; η^2=0.150), and COP Y (p=0.001; η^2=0.247) (Table 2 and 3). Paired-wise comparison demonstrated significantly lower TTP Peak lateral at ACLR (6-month) group than that healthy group (p=0.003, d=1.42, ~43.67 ms). Paired-wise comparison demonstrated a significantly greater TTP Peak medial at ACLR (6-month) group than that healthy group (p=0.008, d=1.20, ~16.47 ms). Paired-wise comparison demonstrated a significantly greater TTP Peak posterior at ACLR (12-month) group than that healthy group (p=0.002, d=1.35, ~21.27 ms). Paired-wise comparison demonstrated a significantly greater TTP Peak anterior at ACLR (6-month) group than that healthy group (p=0.001, d=1.52, ~94.73 ms). Paired-wise comparison demonstrated a significantly greater TTP Active vertical peak at ACLR (6-month) group than that healthy group (p<0.001, d=2.12, ~95.73 ms).

Significant main FOs effects were observed for TTP Peak medial (p=0.002; η^2=0.237), TTP Peak posterior (p=0.037; η^2=0.144), TTP Peak anterior (p<0.001; η^2=0.975), COP X (p=0.038; η^2=0.143), and COP Y (p=0.023; η^2=0.160). Paired-wise comparison demonstrated significantly lower TTP Peak medial at double-density and placebo conditions (p=0.001-0.015, d=0.85-1.45, ~13.53-73.93 ms), TTP Peak posterior at arch-support condition (p=0.028, d=0.72, ~7.33 ms), and TTP Peak anterior at double-density and arch-support conditions (p<0.001, d=1.25-1.89, ~15.47-94.80 ms) than that control condition.

Significant "group-by-FOs" interactions were detected for TTP Peak medial (p=0.002; η^2=0.142), TTP Peak anterior (p=0.004; η^2=0.131), TTP Active vertical peak (p=0.036; η^2=0.099), COP X (p=0.006; η^2=0.126), and COP Y (p=0.004; η^2=0.132). In ACLR (12-month) group (but not in other groups), post-hoc analyses demonstrated lower TTP Peak medial at double-density condition compared with control footwear condition. In ACLR (6-month) group (but not in other groups), post-hoc analyses demonstrated greater TTP Peak anterior at control footwear condition compared with arch-support condition. In healthy group (but not in other groups), post-hoc analyses demonstrated greater COP X excursion at arch-support condition compared with placebo condition.

Table 1. Mean ± standard deviation values for TTP of ground reaction force components and COP excursions during running.

GRF	Healthy group				ACLR Group (6-month)				ACLR Group (12-month)				ACLR Group (18-month)			
	Control shoe	*Placebo*	*Double density*	*Arch support*	*Control shoe*	*Placebo*	*Double density*	*Arch support*	*Control shoe*	*Placebo*	*Double density*	*Arch support*	*Control shoe*	*Placebo*	*Double density*	*Arch support*
TTP Peak lateral (ms)	116.86 ±47.84	129.13 ±54.54	116.73 ±52.10	121.46 ±48.33	185.13 ±144.76	157.73 ±61.49	159.66 ±61.14	145.06 ±73.49	72.93± 56.22	78.00± 32.12	87.73± 46.12	76.66± 46.39	79.33± 39.70	127.60 ±38.05	119.00 ±35.39	98.20± 61.01
TTP Peak medial (ms)	105.80 ±107.58	116.86 ±111.46	32.93± 25.63	69.13± 75.42	33.06± 14.20	59.86± 57.10	46.53± 7.01	49.53± 16.65	35.33± 18.57	31.46± 22.07	32.53± 17.62	72.53± 28.68	32.60± 14.25	35.00± 18.36	35.00± 19.04	80.73± 28.99
TTP Peak posterior (ms)	69.53± 19.30	55.73± 22.22	68.06± 19.45	64.13± 24.13	78.73± 26.71	84.06± 21.05	99.46± 24.11	89.86± 19.64	76.20± 17.57	83.53± 13.77	79.66± 22.52	86.40± 20.12	60.00± 20.50	68.00± 23.10	69.06± 19.76	61.73± 33.36
TTP Peak anterior (ms)	231.53 ±34.66	233.66 ±42.80	217.66 ±74.84	17.95± 4.56	326.46 ±146.78	269.60 ±30.44	227.00 ±84.75	12.74± 3.75	188.93 ±72.08	230.33 ±35.09	229.00 ±31.70	14.87± 4.72	233.20 ±42.34	253.73 ±49.71	248.13 ±54.44	15.84± 2.60
TTP Active vertical peak (ms)	131.00 ±13.14	129.60 ±16.34	133.46 ±10.73	138.66 ±9.67	226.73 ±168.14	145.60 ±38.44	149.53 ±22.89	152.93 ±27.00	120.53 ±31.56	131.66 ±14.56	131.53 ±17.05	130.80 ±15.94	121.86 ±32.22	137.40 ±16.10	138.40 ±20.06	124.46 ±42.47
COP X (mm)	0.06±0.02	0.05±0.02	0.06±0.02	0.05±0.02	0.10±0.05	0.07±0.04	0.09±0.03	0.07±0.04	0.08±0.03	0.07±0.03	0.08±0.03	0.11±0.06	0.06±0.02	0.07±0.02	0.07±0.03	0.07±0.04
COP Y (mm)	0.21±0.11	0.20±0.10	0.20±0.10	0.22±0.12	0.35±0.07	0.31±0.05	0.34±0.03	0.34±0.05	0.31±0.10	0.32±0.13	0.35±0.12	0.36±0.12	0.28±0.13	0.25±0.11	0.30±0.11	0.22±0.11

Data are presented as mean ± standard deviation. BW, body weight; FM, free moment; TTP, time-to-peak; COP, center of pressure; X, medio-lateral direction; Y, anterior-posterior direction; ms, millisecond; mm, millimeter.

Table 3. Statistical results (p-values and partial eta squared) for main and interaction effects on TTP parameters and COP excursions.

GRF	**Main effect of group p (η²)**	**Main effect of foot orthoses p (η²)**	**Main effect of group* foot orthoses p (η²)**
TTP Peak lateral (ms)	**<0.001* (0.326)**	0.497 (0.043)	0.370 (0.055)
TTP Peak medial (ms)	**0.006* (0.199)**	**0.002* (0.237)**	**0.002* (0.142)**
TTP Peak posterior (ms)	**<0.001* (0.299)**	**0.037* (0.144)**	0.050 (0.094)
TTP Peak anterior (ms)	**0.005* (0.203)**	**<0.001* (0.975)**	**0.004* (0.131)**
TTP Active vertical peak (ms)	**0.001* (0.255)**	0.516 (0.041)	**0.036* (0.099)**
COP X (mm)	**0.027* (0.150)**	**0.038* (0.143)**	**0.006* (0.126)**
COP Y (mm)	**0.001* (0.247)**	**0.023* (0.160)**	**0.004* (0.132)**

***:** The level of statistical significance was set at $p < 0.05$. η²: partial eta squared.

Discussions

This longitudinal study examined how post-operative recovery stage and foot orthoses interact to influence the temporal characteristics of GRF and COP trajectories during running in individuals with concurrent ACLR-PF. The findings demonstrate that both recovery duration and orthotic condition systematically influence loading timing and plantar pressure progression, highlighting the prolonged and stage-dependent nature of biomechanical adaptation following ACLR (6).

Recovery-Related Alterations in GRF Timing and COP

Significant main effects of group were observed across all TTP variables, indicating that individuals with ACLR-PF exhibit loading patterns that differ from healthy controls throughout the first 18-month following surgery. Specifically, the 6-month post-ACLR group demonstrated a shorter TTP for lateral GRF and prolonged TTP for medial, anterior, posterior, and active vertical force components. These findings suggest a redistribution of loading timing during stance, characterized by earlier lateral force development and delayed force peaks in the sagittal and vertical directions. Such temporal alterations likely reflect compensatory running strategies during early recovery, where force application is redistributed rather than reduced (6,8). Importantly, in the absence of pre-injury or pre-surgical biomechanical data, these patterns cannot be interpreted as injury-induced deficits (21). Instead, they should be understood as deviations from the kinetic profile of healthy individuals, which may represent either adaptations to surgery or pre-existing movement characteristics. This distinction is critical for avoiding over interpretation of cross-sectional group differences. Altered GRF timing persisted beyond the early rehabilitation phase (6,21). The 12-month post-ACLR group continued to demonstrate a prolonged TTP for posterior force compared with controls, indicating that sagittal-plane braking mechanics may remain altered well into advanced recovery. Although some TTP parameters showed partial convergence toward control values by 18 months, between-group differences were still evident. Together, these findings reinforce the concept that normalization of running biomechanics following ACLR is a prolonged process, extending beyond commonly used return-to-sport timelines (6,21).

Mechanical Effects of FOs on GRF Timing

FOs exerted significant main effects on multiple TTP variables, demonstrating their capacity to modify the temporal structure of external loading during running. Across groups, both active orthoses (arch-support and double-density) were associated with reduced TTP for medial and anterior GRF peaks compared with the control shoe condition. These effects are most plausibly explained by the direct mechanical influence of the orthoses on foot structure and load transmission (11,18). The rigid arch contour of the arch-support orthosis and the medial posting of the double-density orthosis constrain excessive midfoot deformation and rearfoot eversion during early stance (18). By limiting prolonged medial foot collapse, these devices likely facilitate a more rapid progression of plantar loading toward peak values, which is reflected in shorter TTP measures. This interpretation is grounded in the mechanical design of the orthoses and the kinetic outcomes measured in the present study, without invoking unmeasured neuromuscular or sensory mechanisms. Notably, our findings differ from those of studies reporting minimal effects of prefabricated orthoses on GRF timing in heterogeneous injury populations (22). This discrepancy may be attributed to differences in participant characteristics and orthotic design. Individuals with both ACLR-PF present with a specific biomechanical profile that may be more sensitive to orthotic modulation of load distribution and timing, particularly when devices are designed to address pronation-related mechanics (5,18).

FOs and COP Modulation Across Recovery Stages

FOs also demonstrated significant effects on COP excursions, confirming that they alter the spatial progression of plantar pressure during stance. In the healthy group, the arch-support orthosis increased mediolateral COP excursion relative to the placebo condition, suggesting that rigid arch support can accentuate lateral-to-medial load transfer in individuals with intact lower-limb mechanics. This pattern aligns with descriptions of normal COP progression during running (10,11). However, the presence of significant group × orthosis interactions indicates that COP responses to orthotic intervention are not uniform across recovery stages (6,11). In ACLR participants, orthoses did not simply shift COP trajectories toward those of healthy controls. Instead, their effects were modulated by recovery duration, reflecting the interaction between orthotic mechanics and the altered kinetic strategies present at different post-operative phases.

At 12-month post-ACLR, the double-density orthosis was associated with a reduction in medial force TTP, suggesting improved control of frontal-plane loading timing during advanced rehabilitation. This effect is consistent with the mechanical role of medial posting in limiting pronation-related loading patterns (5,18). Conversely, at 6 months post-ACLR, the arch-support orthosis primarily influenced anterior force TTP, indicating a modification of sagittal-plane loading timing during earlier recovery. Importantly, these findings do not imply that one orthosis is superior to another; rather, they demonstrate that different orthotic designs interact differently with recovery-stage-specific loading characteristics.

Clinical and Biomechanical Implications

Collectively, the results suggest that the biomechanical response to FOs following ACLR is recovery-phase dependent (6,18). Orthoses modify how and when forces are applied to the ground and how pressure progresses under the foot, but the nature of these modifications varies according to post-operative duration. These findings underscore the importance of aligning orthotic interventions with the temporal stage of rehabilitation rather than adopting a uniform prescription approach. Future studies incorporating longitudinal pre- and post-surgical measurements, as well as complementary kinematic and neuromuscular data, are needed to further clarify how these kinetic adaptations evolve and how orthotic interventions may be optimized over time.

Limitations

Several limitations should be considered. First, the study focused on male participants to control for sex-specific biomechanical differences, limiting the generalizability of findings to females. Second, the analysis was restricted to kinetics and COP; the underlying joint-level kinematics and muscle activation patterns driving the observed GRF changes remain unexplored. Future research incorporating simultaneous electromyographic and kinematic data is needed to elucidate the specific neuromuscular and biomechanical mechanisms responsible for the altered TTP and COP patterns reported here. Third, the study assessed immediate effects; long-term adaptation studies are needed to determine if these orthotic-induced kinetic changes persist. Finally, the lack of pre-injury biomechanical data limits the interpretation of the observed patterns as being solely injury-induced. Future longitudinal studies should aim to include pre-surgical baselines where possible.

Conclusions

In conclusion, the kinetic effects of FOs following ACLR interact with the post-operative recovery stage. Arch-support and double-density orthoses modify the timing of GRF components and COP pathways, with the specific effects varying between 6- and 12-month post-operative milestones. These findings highlight the importance of considering the recovery timeline when evaluating orthotic interventions from a kinetic perspective.

Research Ethics Statement

The study protocol was conducted in accordance with the Declaration of Helsinki and received full ethical approval from the Ethics Committee of the University of Mohaghegh Ardabili, Ardabil, Iran (Approval Code: IR.UMA.REC.1404.019). The study was prospectively registered with the Iranian Registry of Clinical Trials (Registration No: IRCT20220129053865N2). All participants provided written informed consent prior to data collection, and the assessor was blinded to group allocation and foot conditions to ensure the integrity of the results.

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author Contributions

Ebrahim Piri: Conceptualization, Data Curation, Investigation, Writing – Original Draft. AmirAli Jafarnezhadgero: Project Administration, Supervision, Methodology, Formal Analysis, Writing – Review & Editing. Mahrokh Dehghani: Review & Editing. Afsaneh Enteshari-Moghaddam: Review & Editing. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest Statement

The authors declare that they have no competing interests, financial or otherwise, that could inappropriately influence or bias the findings of this study.

AI Use Statement

During the preparation of this work, the authors did not use any artificial intelligence (AI) tools for writing, structural refinement, or grammatical improvement. All editorial and creative processes were conducted entirely by the authors.

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