American Journal of Clinical and Experimental Medicine
2025, Vol. 13, No. 3, pp. 54-62
https://doi.org/10.11648/j.ajcem.20251303.14

Research Article

Evaluating Gait Dynamics, Contralateral Limb Compensation, and Load Distribution During Ambulation with a Total Contact Cast (TCC): A Comprehensive Biomechanical Analysis

Melanie Violand*, Elijah Goeglein, Mattie Krause, Kathryn Shaw, Evelyn Heigh-Rosen, Tanya Thoms, Jaminelli Banks

Arizona College of Podiatric Medicine, Midwestern University, Glendale, Arizona, USA

Abstract

Background Diabetic foot ulcers represent one of the most persistent and complex complications in clinical management. These ulcers pose significant challenges, often leading to morbidity and impaired mobility. Total contact casts (TCC) are often utilized in treatment for diabetic foot ulcers. A TCC may result in a functional iatrogenic limb length discrepancy (LLD) due to the inherent structure and material composition of the cast. While a TCC is effective in offloading pressure from affected diabetic foot ulcers and promoting healing, it may also alter gait mechanics and pressure distribution, affecting the contralateral limb. Recognizing and addressing these consequences is crucial for developing comprehensive treatment strategies that not only facilitate wound healing but also preserve functional mobility and prevent secondary complications. The central questions guiding this research are: What is the impact of a TCC-induced Leg Length Discrepancy (LLD) on contralateral limb loading? Can a contralateral lift effectively mitigate these effects? *Methods* We conducted a study involving thirty healthy adults (16 female, 14 male; mean age 26.5 years). Gait analysis was conducted using a CAREN instrumented treadmill under four experimental conditions: (1) Baseline: shoes only (no cast or lift); (2) TCC: TCC on the right foot, no lift on the left; (3) TCC+Heel: TCC on the right foot, heel lift in the left shoe; and (4) TCC+Full: TCC on right foot, full-length shoe lift on the left. The TCC introduced an approximate 1.9 cm limb length discrepancy (LLD). Gait parameters and ground reaction forces (GRFs) were recorded and analyzed using repeated-measures ANOVA to assess the effects of TCC and lift conditions on contralateral limb loading. *Results* Key outcomes included walking with a TCC (without a lift) increased peak contralateral foot GRFs by approximately 6% ($p<0.05$), indicating greater stress on the non-casted foot. Introducing a contralateral heel lift significantly reduced contralateral GRFs ($p<0.01$), suggesting partially restoring of normal loading patterns. However, a full-length shoe lift did not provide a comparable reduction in contralateral limb loading, showing no statistically significant benefit. *Significance* This study highlights the importance of recognizing a TCC-induced LLD increases contralateral limb loading. This study demonstrates that a simple contralateral heel lift effectively reduces excess loading and improves gait symmetry, whereas a full-length shoe lift offers little benefit. These findings support the routine use of heel lifts as an adjunctive measure during TCC treatment to improve gait symmetry and protect the non-casted limb.

*Corresponding author: mviola@midwestern.edu (Melanie Violand)

Received: 7 May 2025; **Accepted:** 19 May 2025; **Published:** 18 June 2025

Keywords

Gait, Total Contact Cast, Limb Length Discrepancy, Diabetic Foot Ulcer, Heel Lift

1. Introduction

Diabetes mellitus is a growing global health concern, with diabetic foot ulcers (DFUs) being a major complication of long-standing diabetes [1, 2]. Total contact casts (TCCs) are considered the gold standard for offloading plantar ulcers in diabetic foot patients, as they effectively redistribute plantar pressure and reduce shear forces on the ulcerated foot, thereby facilitating healing [3]. The TCC-EZ®, a prefabricated version of the traditional TCC, is designed to streamline its application while maintaining equivalent offloading efficacy [4].

Despite its benefits, wearing a TCC with its walking boot functionally lengthens the casted limb by approximately 1-2 cm, inducing an iatrogenic leg length discrepancy (LLD). This artificial LLD alters gait mechanics, leading to an asymmetric loading pattern that places greater stress on the contralateral (untreated) limb [5, 6]. The concern is particularly relevant for patients with bilateral diabetic neuropathy, as increased pressure on the non-casted limb may elevate the risk of ulceration or overuse injury [7]. While prior research has confirmed that TCCs significantly offload plantar pressure from the ulcerated foot [8], fewer studies have focused on the compensatory increase in loading on the contralateral foot—a potential concern in preventing secondary ulcers or musculoskeletal strain.

Even mild LLDs (as small as 5-10 mm) have been shown to significantly alter gait mechanics, increasing postural sway, asymmetric weight distribution, and joint loading [9, 10]. Severin et al. found that wearing an orthopedic walking boot—simulating an LLD—induced changes in joint mechanics: however, adding a heel lift helped improve hip moment equilibrium and limb symmetry [11]. These findings suggest that simple contralateral shoe modifications (such as heel lifts or full-length shoe inserts) may help mitigate the biomechanical impact of TCC-induced LLDs.

Several studies have analyzed gait with one limb immobilized. Shaw et al. demonstrated that TCC use significantly reduces peak plantar pressures on the casted foot [12], and Zhang et al. reported that walking in a short-leg cast boot did not increase the ground reaction forces (GRFs) experienced by the booted limb [5]. Similarly, Theodorakos et al. found that applying a TCC did not significantly increase peak joint loads at the knee or hip of the casted limb [6], implying that any additional loading must be absorbed elsewhere—likely by the contralateral limb. However, the specific effects on the contralateral foot remain underexplored.

One of the few studies that examined contralateral limb loading during TCC use was conducted by Armstrong et al., who used dynamic pressure mapping and observed notable changes in plantar pressure distribution on the non-casted foot [13]. However, comprehensive data on ground reaction forces and effective interventions remain limited.

Given the potential risk of contralateral overloading and ulceration, it is critical to determine how TCC-induced LLD affects the opposite limb and whether simple compensatory interventions can mitigate any harmful effects. Prior studies on structural LLD (rather than cast-induced LLDs) suggest that heel lifts and full-length shoe inserts can improve gait symmetry and reduce biomechanical stress [14]. Internal heel lifts are typically limited to ~10 mm due to shoe fit constraints, whereas full-length shoe lifts provide more extensive height correction but may alter gait mechanics differently [15].

2. Methods

2.1. Study Objective and Hypothesis

Building on these insights, this study investigates gait changes induced by a TCC, with a specific focus on the contralateral (untreated) limb. We assess whether compensatory heel lifts or full-length shoe lifts can reduce the increased contralateral plantar forces associated with TCC-induced LLD. Our hypotheses are as follows:

1) Walking in a TCC will significantly increase contralateral limb loading, as reflected by increased peak GRFs on the non-casted foot.
2) A heel lift will significantly reduce contralateral GRFs, partially restoring normal loading patterns.
3) A full-length shoe lift will have less impact compared to the heel lift in reducing contralateral GRFs, due to its distinct impact on foot mechanics.

By quantifying these biomechanical effects, our study aims to provide clinical insights into optimizing offloading strategies for TCC users, improving gait symmetry and minimizing secondary injury risks in patients undergoing DFU treatment.

2.2. Study Design and Participants

We conducted a controlled, repeated-measures biomechanical study using healthy adult volunteers, with each participant serving as their own control. A total of 30 participants (16 females, 14 males; mean age 26.53 years, height 1.72 m, weight 74.19 kg) were enrolled.

2.3. Inclusion Criteria

Ability to walk on a treadmill for at least 10 minutes, both with and without a TCC.

2.4. Exclusion Criteria

History of lower-extremity injury, gait abnormalities, or neurological/musculoskeletal conditions affecting walking.

All participants wore their athletic shoes during testing. Written informed consent was obtained before participation, and the study was approved by the Institutional Review Board (IRB).

Table 1. *Participant Demographics (N = 30).*

Age (years)	Height (m)	Weight (kg)	Sex
Mean: 26.53	Mean: 1.72	Mean: 74.19	16 Female, 14 Male
Range: 24-34	Range: 1.55-1.85	Range: 52.16-165.00	—

2.5. Experimental Conditions

Each participant performed gait trials under four conditions, tested in a fixed sequence to reflect progression from normal walking to TCC use and subsequent interventions:

1) Baseline: Normal walking with athletic shoes on both feet (no cast, no lifts).
2) TCC (No Lift): TCC-EZ® cast applied to the right lower extremity, with an athletic shoe only on the left (contralateral) foot, without a lift.
3) TCC + Heel Lift: TCC-EZ® on the right, plus a heel lift inserted inside the left shoe (to partially compensate for the LLD).
4) TCC + Full-Length Lift: TCC-EZ® on the right, plus a full-length external shoe lift applied to the outsole of the left shoe (to fully compensate for the LLD).

The same proprietary TCC system (TCC-EZ®, MedE©) was applied to all participants by a trained clinician, following manufacturer guidelines [4].

2.6. Limb Length Discrepancy Measurement and Shoe Lift Fitting

Upon TCC application, the cast and its rigid walking boot effectively lengthened the right limb, creating an iatrogenic LLD. We measured this discrepancy immediately post-TCC application by recording the distance from the anterior superior iliac spine (ASIS) to the floor at the first metatarsophalangeal (MTP) joint on both limbs. The TCC-EZ® created an average limb length increase of ~1.9 cm compared to the contralateral (left) leg.

To accommodate the LLD, participants received contralateral shoe lifts of appropriate height:

2.6.1. Heel Lift Condition (Internal Lift)

1) Inserted inside the left shoe, under the heel.
2) Heights: 0 cm (control), 0.5 cm, or 1.0 cm (chosen to best match each participant's LLD, rounded to the nearest available option).

2.6.2. Full-Length Shoe Lift Condition (External Lift)

1) Placed on the outsole of the left shoe (raising the entire foot).
2) Heights: 0 cm (control), 0.9 cm, 1.4 cm, 1.7 cm, or 2.1 cm (selected based on individual LLD and shoe size feasibility).

This two-step intervention allowed testing of both: Minimal compensation (heel lift inside the shoe) Maximal compensation (full shoe lift)

Participants were secured with a ceiling-mounted safety harness during all trials for fall protection.

2.7. Data Collection and Processing

All gait trials were conducted using a Computer Assisted Rehabilitation Environment (CAREN) dual-belt instrumented treadmill (Motek Medical, Amsterdam, NL) [16]. The CAREN system provides an immersive, controlled testing environment with embedded dual force plates under each belt, enabling precise ground reaction force and spatiotemporal gait parameter collection [16]. This setup allowed real-time force measurements for both limbs without requiring separate force platforms.

For each trial condition, participants walked at their self-selected speed with an initial acclimation period, followed by a data collection period:

2.7.1. Baseline (Condition 1 - Normal Shoes)

1) Acclimation: ~2 minutes of walking to adapt to the treadmill.
2) Data Collection: 1 minute of steady-state walking.

2.7.2. TCC (Condition 2 - Unaccommodated LLD)

1) Acclimation: ~2 minutes of walking after applying the TCC-EZ®.
2) Data Collection: 1 minute of steady-state walking.

2.7.3. TCC + Heel Lift (Condition 3 - Partial LLD Correction)

1) Acclimation: ~30 seconds after inserting the heel lift into the left shoe.
2) Data Collection: 1 minute of steady-state walking.

2.7.4. TCC + Full-Length Lift (Condition 4 - Full LLD Correction)

1) Acclimation: ~30 seconds after applying the full-length external lift to the left shoe.
2) Data Collection: 1 minute of steady-state walking.

During each trial, the CAREN system's motion-capture sensors and force plates recorded:

1) Ground reaction forces (GRFs): Left (contralateral) and right (casted) limbs.
2) Peak vertical GRF: Primary outcome (contralateral limb loading).
3) Peak combined GRF: Vector sum of vertical and fore-aft forces (total loading).
4) Spatiotemporal gait parameters: Walking speed, stride length, single-limb support time, and double-support time.

Data was processed using the CAREN software to calculate mean values for each outcome over the 1-minute trial. Each participant's results for all four conditions were compiled for statistical analysis.

2.8. Statistical Analysis

This study utilized a within-subjects (repeated-measures) design to compare gait parameters across conditions.

One-way repeated-measures ANOVA was conducted for each outcome variable (GRFs, stride length, support times) to test for overall differences across conditions (Baseline, TCC, TCC+Heel, TCC+Full).

2.8.1. If the ANOVA Showed a Significant Condition Effect, Post-hoc Paired t-tests Were Conducted for Planned Comparisons

1) TCC (no lift) vs. TCC + Heel Lift → Evaluates partial LLD compensation.
2) TCC (no lift) vs. TCC + Full-Length Lift → Evaluates full LLD compensation.
3) Baseline vs. TCC (no lift) → Confirms the effect of wearing the TCC itself.
4) TCC + Heel vs. TCC + Full-Length Lift → Determines if one intervention is superior.

2.8.2. Statistical Significance & Confidence Intervals (CIs)

1) Significance threshold: $p < 0.05$.
2) Mean differences ± standard deviation (SD) reported for paired comparisons.
3) 95% Confidence Intervals (CIs) were calculated—if a CI did not include zero, the difference was considered statistically significant.

2.8.3. Software Used

All statistical analyses were conducted using SPSS v27 (IBM Corp.)

3. Results

3.1. Spatiotemporal Gait Changes

Applying the TCC had measurable effects on spatiotemporal gait parameters, although the changes were relatively small and did not reach statistical significance. With the right leg immobilized in a TCC (uncompensated by any lift), participants exhibited a slight reduction in stride length on the left (contralateral) side compared to Baseline. The average stride length decreased from 1.34 m at Baseline to 1.32 m in the TCC (No Lift) condition (*mean change: -0.02 m, $p = 0.28$*).

Similarly, double-support time per gait cycle decreased by ~0.01 s (from 0.278 s at Baseline to 0.268 s with the TCC, $p = 0.34$), indicating a trend toward reduced time with both feet on the ground. This suggests a minor increase in single-limb support time on each leg when wearing the cast. However, neither the stride length nor support time differences were statistically significant, indicating that walking speed and cadence remained largely unaffected by the cast.

Thus, our hypothesis (H1) was only partially supported—qualitatively, the TCC tended to reduce stride length and alter support times, but these changes were small and not statistically significant in a healthy cohort.

3.2. Contralateral Limb Loading (Ground Reaction Forces - GRF)

Unlike the modest spatiotemporal changes, wearing a TCC had a clear and statistically significant impact on contralateral limb loading.

When participants ambulated with the TCC (without any lift on the contralateral side), the peak ground reaction forces (GRFs) on the left foot increased significantly compared to Baseline.

1) Peak vertical GRF on the left foot increased by ~6% (from 744.3 N at Baseline to 791.3 N in the TCC No Lift condition, $p < 0.01$).
2) Peak combined (resultant) GRF also increased by ~6% (from 750.1 N at Baseline to 796.2 N in the TCC No Lift condition).

These results confirm that H1 was supported in terms of force—walking in a TCC without compensation significantly increased contralateral limb loading.

3.3. Effect of a Heel Lift (TCC + Heel Condition)

Introducing a contralateral heel lift significantly reduced the excess force on the left foot:

1) Mean peak vertical GRF on the left decreased by 12.66 N (p = 0.006) with the heel lift.
2) Mean peak combined GRF decreased by 13.93 N (p = 0.013).

This statistically significant offloading effect confirms that the heel lift helped mitigate contralateral limb loading, supporting H2. However, forces remained ~3-5% higher than Baseline, meaning that while the heel lift partially alleviated the increased load, it did not fully restore contralateral forces to normal levels.

3.4. Effect of a Full-Length Lift (TCC + Full-Length Lift Condition)

In contrast, the full-length shoe lift did not significantly change contralateral loading.

1) Mean peak vertical GRF in the TCC + Full condition was 795.1 N (statistically similar to 791.3 N with No Lift, p = 0.535).
2) Mean peak combined GRF was also unchanged (796.2 N vs. 799.9 N, p = 0.61).

This means that the full-length lift was not effective in reducing contralateral limb loading, supporting H3. One possible explanation is that the weight, thickness, or altered proprioception of the full-length lift may have negated any biomechanical benefits.

Neither type of lift was able to fully restore contralateral GRFs to baseline, but only the heel lift produced a significant reduction.

Table 2. Summary of Contralateral GRF Results.

Condition	Peak Combined GRF (Mean ± SD) [N]	Peak Vertical GRF (Mean ± SD) [N]
Baseline (Athletic Shoes Only, N=30)	750.1 ± 140.7	744.3 ± 138.8
TCC (No Lift) (TCC-EZ® on Right, No Lift on Left, N=30)	796.2 ± 150.9*	791.3 ± 149.3*
TCC + Heel Lift (TCC-EZ® + Heel Lift on Left, N=30)	810.1 ± 157.7*	803.9 ± 155.4*
TCC + Full-Length Lift (TCC-EZ® + Full Lift on Left, N=30)	799.9 ± 153.0	795.1 ± 150.3

* ($p < 0.05$ compared to Baseline.)
The TCC (No Lift) condition resulted in significantly higher contralateral GRFs compared to Baseline ($p < 0.01$).
The TCC + Heel condition significantly reduced contralateral GRFs compared to No Lift ($p = 0.006$).
The TCC + Full condition did not significantly change contralateral GRFs compared to No Lift ($p > 0.5$).

Table 3. Paired t-test Comparisons of Contralateral Peak GRFs.

Comparison	t-value	df	95% CI of Difference	p-value	Mean Difference
TCC No Lift vs. TCC + Heel Lift (Contralateral Peak GRF Reduction)	-2.96	29	(-21.40, -3.91)	0.006	-12.66 N
TCC No Lift vs. TCC + Heel Lift (Combined GRF Reduction)	-2.66	29	(-24.65, -3.21)	0.013	-13.93 N
TCC No Lift vs. TCC + Full-Length Lift (Contralateral Peak GRF Reduction)	-0.63	29	(-16.15, 8.56)	0.535	-3.79 N
TCC No Lift vs. TCC + Full-Length Lift (Combined GRF Reduction)	-0.51	29	(-18.64, 11.20)	0.610	-3.72 N

A significant reduction in contralateral peak GRF was observed with the Heel Lift ($p < 0.05$).
The Full-Length Lift did not significantly reduce contralateral peak GRFs ($p > 0.5$).

3.5. Key Findings

1. Wearing a TCC without any compensation significantly increased contralateral limb loading, with a ~6% increase in peak force.
2. Introducing a contralateral heel lift significantly reduced contralateral peak GRFs by ~12-14 N ($p < 0.01$).
3. The full-length shoe lift, however, did not lead to a significant reduction in contralateral GRFs.
4. While neither intervention fully restored forces to baseline levels, the heel lift demonstrated a measurable benefit in offloading the contralateral limb.

These findings highlight the heel lift is a simple yet effective intervention to reduce excessive contralateral loading during TCC ambulation [8, 9, 17, 18].

4. Discussion

The use of a total contact cast (TCC) is a well-established intervention for offloading plantar pressure in patients with diabetic foot ulcers (DFUs). Our findings confirm that while a TCC (specifically the TCC-EZ®) effectively offloads pressure from the injured foot, it also creates a significant leg length discrepancy (LLD). This LLD alters gait dynamics and places increased stress on the contralateral limb.

4.1. Contralateral Limb Loading and Clinical Implications

In this study, ambulating with a TCC resulted in a significant increase in peak ground reaction forces (GRFs) on the contralateral limb (Table 2). Specifically, contralateral peak GRFs increased by approximately 6% compared to baseline. This finding is clinically significant because many patients with diabetes and neuropathy are often at risk for ulceration in both feet [3, 4].

1) Excessive loading on the unaffected foot may lead to the development of ulcers, stress fractures, or musculoskeletal strain, thereby increasing the risk of secondary complications.
2) Clinicians should be aware of this unintended effect of TCC use and consider incorporating strategies such as use of orthotic devices or footwear adjustments, to mitigate stress on the contralateral limb.

4.2. Effectiveness of a Contralateral Heel Lift

A key finding of this study is that a simple contralateral heel lift can significantly reduces contralateral foot loading.

1) Adding a 0.5-1 cm heel lift resulted in reduction of contralateral peak GRFs by ~2-3%, a statistically significant improvement (Table 3).
2) These findings are consistent with prior research on anatomical LLD, where heel lifts have been shown to improve gait mechanics and distribute weight more evenly [10, 19].
3) The heel lift likely improved gait symmetry by minimizing the functional asymmetry induced by the TCC, thus offloading the contralateral limb more effectively.

4.3. Why Did the Full-Length Lift Not Help

Interestingly, the full-length shoe lift did not produce the same offloading benefit as the heel lift (Table 3). Several potential explanations may account for this:

1) Heel Lift vs. Full Lift Mechanism - The heel lift, placed inside the shoe, likely altered foot mechanics during the stance phase, promoting a smoother rollover on the short limb [20, 21]. In contrast, the full-length lift raised the entire foot uniformly, which may not have corrected the altered biomechanics in the same way, potentially limiting its effectiveness.
2) Proprioception and Stability Factors - Some participants might have felt less stable with the full-length lift, leading to a more cautious gait, that negated any potential biomechanical benefits [22].
3) Unintended Changes in Gait Timing - The full-length lift may have subtly altered gait timing, such as delaying forefoot loading or influencing postural control differently than anticipated. These changes could have interfered with the intended corrective effect on contralateral limb loading.

While further research is needed, our findings suggest that a simple, lightweight heel lift may be more effective than a full-length shoe lift for mitigating contralateral loading during TCC ambulation.

4.4. Comparison with Prior Studies

Our study's findings contribute to and expand upon the existing body of literature regarding gait compensation for leg length discrepancies.

1) Bangerter et al. showed that shoe lifts improved gait symmetry and spinal alignment in adolescents with structural LLD, highlighting the potential for corrective interventions in gait mechanics [15].
2) Lavery et al. demonstrated that reducing dynamic plantar pressures through offloading interventions improves outcomes in patients with diabetic foot ulcers, underscoring the importance of load redistribution [8].
3) Armstrong et al. examined contralateral foot pressures in TCC users and found lower contralateral pressures compared to normal walking [13]. However, our study diverges from their findings by demonstrating a significant increase in contralateral limb loading when using a TCC without compensation.

4.5. Why Do Our Results Differ from Armstrong et al

One potential explanation for the discrepancy between our findings and those of Armstrong et al. lies in the use of assistive devices:

1) Armstrong's study included patients using crutches, which likely unloaded both feet, leading to different pressure distributions and potentially reducing contralateral limb loading [13].
2) In contrast, our study simulated full weight-bearing conditions without external support, providing a more accurate representation of real-world TCC ambulation.

Furthermore, our use of the CAREN system enabled high-fidelity, controlled data collection, eliminating environmental variability and offering novel insights into contralateral limb loading during TCC use.

5. Clinical and Research Implications

5.1. Clinical Takeaways

The findings from this study have important implications for clinical practice:

1) Contralateral heel lift consideration: Clinicians should consider incorporating a contralateral heel lift when prescribing a TCC to reduce contralateral foot strain.
2) Small heel lift benefits: Even a modest heel lift (0.5-1 cm) can significantly reduce peak ground reaction forces, potentially helping to prevent secondary ulcers or overuse injuries in diabetic patients.
3) Full-length lift limitations: The full-length shoe lift did not provide significant offloading, indicating that heel lifts may be a more practical and effective intervention for managing contralateral limb stress during TCC ambulation.

5.2. Future Research Directions

While this study provides valuable biomechanical insights, further research is essential to deepen our understanding and address key questions:

1) Examine long-term outcomes: Investigate whether consistent use of a heel lift during TCC treatment can reduce ulceration rates and improve long-term outcomes for patients with diabetic foot ulcers in real-world settings.
2) Assess patient-reported comfort and adherence: Explore how different lift types impact patient comfort, adherence, and overall satisfaction, as some individuals may prefer a full-length lift despite its biomechanical drawbacks.
3) Expand to clinical populations: While our study focused on healthy adults, it is crucial to assess how diabetic patients, particularly those with neuropathy, balance impairments, or wound pain, respond to heel lifts and TCC interventions.
4) Compare treadmill vs. overground walking: Although the CAREN system provided controlled walking conditions, future studies should investigate how gait dynamics differ during real-world, overground walking versus treadmill-based assessments.

5.3. Study Strengths and Limitations

5.3.1. Strengths

1) Controlled Study Design - Each participant served as their own control, reducing inter-subject variability and allowing for a more accurate comparison of conditions.
2) Advanced Gait Analysis - The use of CAREN system provided high-precision measurement of force and motion, ensuring the reliability and accuracy of the gait data.
3) Novelty - To our knowledge, this is the first study to assess contralateral GRFs in TCC users with and without shoe lifts, offering new insights into gait compensation strategies.

5.3.2. Limitations

1) Healthy Participants Only - Our sample consisted of young, healthy adults. As such, the findings may not be directly applicable to older adults, individuals with neuropathy or diabetic foot ulcers, who may have different gait mechanics.
2) Short-Term Assessment - The study focused on immediate gait adaptations. The long-term effects of TCC use and the sustained impact of shoe lifts (e.g., over several weeks of TCC use) remain unknown.
3) Treadmill-Based Testing - Although all conditions were compared under controlled treadmill conditions, gait mechanics may differ during real-world, overground walking [20].

Despite these limitations, this study provides valuable, novel, quantitative evidence on contralateral foot loading during TCC ambulation and demonstrates the effectiveness of a simple, practical intervention to mitigate excess force.

6. Conclusion

This study confirms that wearing a TCC significantly increases peak forces on the contralateral limb, thereby elevating the risk of secondary complications in patients with diabetic foot ulcers.

1) Adding a 0.5-1 cm contralateral heel lift significantly reduced these forces and improved gait symmetry, offering a practical solution to mitigate excess limb stress.
2) A full-length shoe lift did not produce significant offloading benefits for the contralateral limb. These findings suggest that clinicians should consider prescribing a contralateral heel lift alongside TCC treatment to help

reduce contralateral limb stress and enhance overall gait mechanics.

Future studies should aim to validate these findings in patients with diabetes and DFUs, evaluate long-term adherence to heel lifts, and explore real-world overground walking adaptations.

By addressing the unintended effects of TCC-induced limb asymmetry, we can optimize offloading strategies for DFU patients, reduce the risk of secondary ulcers and enhance mobility outcomes.

Abbreviations

DFU	Diabetic Foot Ulcer
TCC	Total Contact Cast
LLD	Limb Length Discrepancy
GRF	Ground Reactive Forces
IRB	Institutional Review Board
CAREN	Computer Assisted Rehabilitation Environment

Acknowledgments

We would like to thank Bill Denton, Biomedical Engineer at Midwestern University for his contributions with the application of the CAREN system and data collection. We would like to thank Charlotte Bolch, Associate Director for the Office of Research and Sponsored Programs at Midwestern University for her statistical analysis and reporting.

Author Contributions

Melanie Violand: Conceptualization, Investigation, Methodology, Resources, Supervision, Visualization, Writing - original draft, Writing - review & editing

Elijah Goeglein: Conceptualization, Investigation, Methodology, Resources, Supervision, Visualization, Writing - original draft, Writing - review & editing

Mattie Krause: Investigation, Visualization, Writing - original draft, Writing - review & editing

Kathryn Shaw: Investigation, Visualization, Writing - original draft, Writing - review & editing

Evelyn Heigh-Rosen: Investigation, Writing - original draft, Writing - review & editing

Tanya Thoms: Investigation, Visualization, Writing - original draft, Writing - review & editing

Jaminelli Banks: Investigation, Visualization, Writing - original draft, Writing - review & editing

Funding

This project was funded exclusively by intramural funding provided by Midwestern University Arizona College of Podiatric Medicine.

Data Availability Statement

The corresponding author can provide the datasets used and analyzed in this study upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Schaper, N. C., van Netten, J. J., Apelqvist, J., Bus, S. A., Hinchliffe, R. J., & Lipsky, B. A. (2019). IWGDF practical guidelines on prevention and management of diabetic foot disease (2019 revision). Available from: https://iwgdfguidelines.org/wp-content/uploads/2019/05/01-IWGDF-practical-guidelines-2019.pdf (Accessed Jan 2024).

[2] Malhotra, S., Bello, E., & Kominski, S. (2012). Diabetic foot ulcerations: biomechanics, Charcot foot, and total contact cast. *Seminars in Vascular Surgery, 25*(2), 66-69. https://doi.org/10.1053/j.semvascsurg.2012.05.001

[3] Begg, L. (2016). Total contact cast wall load in patients with a plantar forefoot ulcer and diabetes. *Journal of Foot and Ankle Research, 9*(1), 1-8. https://doi.org/10.1186/s13047-015-0119-0

[4] Bhatt, U. K., Foo, H. Y., McEvoy, M. P., Tomlinson, S. J., Westphal, C., Harrison, J. C., et al. (2021). Is TCC-EZ® a suitable alternative to gold standard total-contact casting? *Journal of the American Podiatric Medical Association, 111*(5), Article 1. https://doi.org/10.7547/8750-7315-111-5.Article_1

[5] Zhang, S., Clowers, K. G., & Powell, D. (2006). Ground reaction force and 3D biomechanical characteristics of walking in short-leg walkers. Gait & Posture, 24(4), 487-492. https://doi.org/10.1016/j.gaitpost.2005.12.003

[6] Theodorakos, I., Healy, A., Chockalingam, N., et al. (2022). Assessment of the effect of a total contact cast on lower limb kinematics and joint loading. Gait & Posture, 98, 203-209. https://doi.org/10.1016/j.gaitpost.2022.09.075

[7] Hartsell, H. D. (2002). Total contact casting: Its effect on contralateral plantar foot pressure. *Journal of Foot and Ankle Research.* https://doi.org/10.1177/107110070202300407

[8] Lavery, L. A., Vela, S. A., Lavery, D. C., & Quebedeaux, T. L. (1996). Reducing dynamic foot pressures in high-risk diabetic subjects with foot ulcerations: A comparison of treatments. *Diabetes Care, 19*(8), 818-821. https://doi.org/10.2337/diacare.19.8.818

[9] Khamis, S., & Eli, C. (2018). The effect of simulated leg length discrepancy on lower limb biomechanics during gait. *Gait & Posture, 61*, 73-80. https://doi.org/10.1016/j.gaitpost.2017.12.024

[10] Eliks, M., Ostiak-Tomaszewska, W., Lisiński, P., & Koczewski, P. (2017). Does structural leg-length discrepancy affect postural control? Preliminary study. *BMC Musculoskeletal Disorders, 18*(1), 346. https://doi.org/10.1186/s12891-017-1707-x

[11] Severin, A. C., Gean, R. P., Barnes, S. G., Queen, R. M., Butler, R. J., & Martin, R. L. (2019). Effects of a corrective heel lift with an orthopedic walking boot on joint mechanics and symmetry during gait. *Gait & Posture, 73*, 233-238. https://doi.org/10.1016/j.gaitpost.2019.07.374

[12] Shaw, J. E., Hsi, W. L., Ulbrecht, J. S., Norkitis, A., Becker, M. B., & Cavanagh, P. R. (1997). The mechanism of plantar unloading in total contact casts: Implications for design and clinical use. Foot & Ankle International, 18(12), 809-817. https://doi.org/10.1177/107110079701801210

[13] Armstrong, D. G., Liswood, P. J., & Todd, W. F. (1995). Contralateral limb during total contact casting: A dynamic pressure and thermometric analysis. *Journal of the American Podiatric Medical Association, 85*(12), 733-737. https://doi.org/10.7547/87507315-85-12-733

[14] Tirtashi, F. H., Eslami, M., & Taghipour, M. (2022). Effect of shoe insole on the dynamics of lower extremities in individuals with leg length discrepancy during walking. Journal of Bodywork and Movement Therapies, 31, 51-56. https://doi.org/10.1016/j.jbmt.2022.03.006

[15] Bangerter, C. J., Romkes, J., Lorenzetti, S., Krieg, A. H., Hasler, C. C., Brunner, R., et al. (2019). What are the biomechanical consequences of a structural leg length discrepancy on the adolescent spine during walking? *Gait & Posture, 68*, 506-513. https://doi.org/10.1016/j.gaitpost.2018.12.040

[16] Motek Medical. CAREN (Computer Assisted Rehabilitation Environment). Available from: https://www.motekmedical.com/solution/caren/ (Accessed Jan 2024).

[17] Kaufman, K. R., Miller, L. S., & Sutherland, D. H. (1996). Gait asymmetry in patients with limb-length discrepancy. *Journal of Pediatric Orthopaedics, 16*(2), 144-150. https://doi.org/10.1097/00004694-199603000-00002

[18] Khamis, S., & Carmeli, E. (2017). Relationship and significance of gait deviations associated with limb length discrepancy: A systematic review. *Gait & Posture, 57, 115-123.* https://doi.org/10.1016/j.gaitpost.2017.05.028

[19] Defrin, R., Benyamin, S., Aldubi, R. D., & Pick, C. G. (2005). Conservative correction of leg-length discrepancies of 10 mm or less for the relief of chronic low back pain. *Archives of Physical Medicine and Rehabilitation, 86*(11), 2075-2080. https://doi.org/10.1016/j.apmr.2005.06.012

[20] Gates, D. H., Darter, B. J., Dingwell, J. B., & Wilken, J. M. (2012). Comparison of walking overground and in a Computer Assisted Rehabilitation Environment (CAREN) in individuals with and without transtibial amputation. *Journal of NeuroEngineering and Rehabilitation, 9*, 81. https://doi.org/10.1186/1743-0003-9-81

[21] Gross, M. T. (1987). Effects of recurrent lateral ankle sprains on active and passive judgments of joint position. *Physical Therapy, 67*(10), 1505-1509. https://doi.org/10.1093/ptj/67.10.1505

[22] Gurney, B. (2002). Leg length discrepancy. *Gait Posture.* 15(2): 195-206. https://doi.org/10.1016/s0966-6362(01)00148-5