



# Prosthetic Gait Asymmetry: Long-Term Orthopedic Consequences for the Intact Limb

Journal: Journal of Movement Mechanics & Biomechanics Science (JMMBS), ISSN (Online): 3070-3662

Volume: 2 | Issue: 2 | Year: 2026

## Authors and Affiliations:

**Dr. Neeraj Mehta, PhD**, *MMSx Authority Institute for Movement Mechanics & Biomechanics Research, Powell, Ohio, USA.* <https://orcid.org/0000-0001-6200-8495>

**Dr José Luis Parreño Catalán**, Director Departamento Biomecánica. Doctor (PhD) en Medicina y Cirugía (Cum Laude) (USC), Universidad de Santiago de Compostela, Santiago de Compostela, Spain

**Alireza Fatahian**, Affiliation: Department of Nutrition and Movement Sciences (NUTRIM), Maastricht University, Netherlands. ORCID: 0000-0002-7554-2475

**Dr. Darinka Korovljević, PhD**, *Faculty of Sport and Physical Education, University of Novi Sad, Serbia.* ORCID: 0000-0002-2510-3044

**Dr. Masumeh Baghban**, Department of Sports Biomechanics & Rehabilitation, Kinesiology Research Center, Kharazmi University, Tehran, Iran. ORCID: 0000-0002-9828-5723

**Dr. Swapnesh Tiwari, MD, MS**, *Department of Population Health, CVS Health, USA.* ORCID: 0009-0001-9271-1162

**Nesrine Adhadhii**, PhD Biomechanics and Physiology of Exercise, ISSEP Kef, Al Asimah, Kuwait, ORCID ID: 0009-0001-7842-5696

**Dr. Steve Henderson, PhD** *MMSx Authority Institute for Movement Mechanics & Biomechanics Research, USA.* ORCID: 0009-0005-7485-1427

Article ID: JMMBS-2026-004-v2-i2

JMMBS ID: JMMBS-2026-004-PGAL-V2-I2

IMSO ID: IMSO-REG-20260219-RS-5997-PGA

DOI: <https://doi.org/10.66078/jmmbs.v2i2.004>

**Licence:** This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0).



**Conflict of Interest:** The authors declare no competing interests.

**Funding :** No external funding was received.

### Abstract

**Background:** Prosthetic gait asymmetry is commonly treated as a functional limitation; however, its long-term orthopedic consequences on the intact limb remain under-recognized. This study investigates how chronic asymmetrical loading patterns influence degenerative risk in unilateral lower-limb amputees.

**Methods:** Nineteen individuals with unilateral transtibial amputation (16 male, 3 female; age  $49.5 \pm 11.3$  years) participated in a 12-month longitudinal study. Gait analysis was performed at baseline, 6 months, and 12 months using force plates and 3D motion capture. We analyzed temporal symmetry (stance time ratio), force symmetry (vertical ground reaction force [vGRF] ratio), intact limb joint moments, and clinical outcomes (WOMAC pain scores, radiographic Kellgren-Lawrence [KL] osteoarthritis grade).

**Results:** Over 12 months, significant deleterious changes were observed despite some participants improving temporal symmetry. Force symmetry significantly worsened ( $0.701 \rightarrow 0.663$ ;  $p < 0.001$ ), while intact limb knee flexion and adduction moments significantly increased by 6.6% and 7.7%, respectively ( $p < 0.001$ ). WOMAC pain scores increased by 26.4% ( $p = 0.0001$ ). VAS pain increased by 34.0% ( $p = 0.0003$ ). Baseline force symmetry was significantly correlated with baseline knee flexion moment ( $r = 0.479$ ,  $p = 0.038$ ). Notably, subjects with improved inter-limb temporal symmetry but unresolved force asymmetry continued to demonstrate elevated intact-limb tissue stress.

**Conclusion:** These findings emphasize that restoring visual or temporal gait symmetry is insufficient without addressing underlying mechanical load distribution. Compensatory strategies—particularly increased intact-side stance time, vertical loading rate, and frontal-plane knee moments—are more predictive of **osteoarthritic risk trajectory** than prosthetic design alone. The study supports biomechanically informed prosthetic tuning and neuromuscular retraining strategies aimed at protecting the intact limb over the lifespan.



## Introduction

The rehabilitation of individuals with lower-limb amputation has traditionally focused on restoring functional mobility and achieving a visually symmetric gait pattern. While modern prostheses have made remarkable strides in this regard, a growing body of evidence suggests that a visually appealing gait may mask persistent and dangerous asymmetries in mechanical loading [1, 2]. This chronic overloading of the intact limb is a significant clinical concern, as it is strongly implicated in the high prevalence of secondary musculoskeletal conditions, most notably osteoarthritis (OA) of the knee and hip [3, 4].

A foundational review by Gailey et al. (2008) highlighted that individuals with lower-limb amputation often favor and stress their intact limb, leading to degenerative changes over time [5]. Subsequent research has consistently demonstrated this phenomenon. Studies using force plate analysis have shown that the intact limb can experience 30-50% greater peak vertical ground reaction forces (vGRF) and over 150% greater peak knee flexion moments compared to the prosthetic limb during daily activities like walking and sit-to-stand transfers [6, 7]. This disparity is largely attributed to the functional limitations of conventional prostheses, which lack the powered push-off and variable stiffness of a biological ankle, forcing the user to adopt compensatory strategies [8, 9].

These compensatory mechanisms, while necessary for ambulation, come at a significant orthopedic cost. The increased loading on the intact limb, particularly the elevated knee adduction moment (KAM)—a well-established surrogate for medial compartment knee loading and a strong predictor of OA progression [10, 11]—creates a biomechanical environment ripe for cartilage degradation. Lloyd et al. (2010) established a moderate relationship between strength asymmetry and OA risk factors, suggesting that muscular imbalances further exacerbate the mechanical loading problem [12].

Despite this understanding, a critical gap remains in the literature. Most studies are cross-sectional, capturing only a single snapshot of gait, and few have longitudinally tracked both biomechanical and clinical indicators of OA progression in the same cohort. It is therefore unclear how these asymmetries evolve over time and which specific biomechanical factors are most predictive of long-term joint degeneration. Furthermore, there is a clinical tendency to prioritize temporal symmetry (e.g., equal step times), with the assumption that this will normalize kinetic (force) parameters. The validity of this assumption has not been rigorously tested.

This study aims to address these gaps through a 12-month longitudinal investigation of 19 individuals with unilateral transtibial amputation. We hypothesize that: 1) baseline force asymmetry will be more strongly correlated with indicators of joint loading (e.g., knee moments) than temporal asymmetry; and 2) a decline in force symmetry over 12 months will be associated with a corresponding increase in intact limb joint moments and a worsening of clinical pain and radiographic OA status. By examining the interplay between temporal symmetry, force symmetry, and long-term joint health, we seek to provide a more nuanced, biomechanically informed framework for prosthetic rehabilitation that prioritizes the preservation of the intact limb.

## Methods

### Participants

Nineteen individuals with unilateral transtibial amputation were recruited from local rehabilitation clinics. The cohort included 16 males and 3 females with a mean age of  $49.5 \pm 11.3$  years. All participants were at least two years post-amputation (mean  $5.1 \pm 1.6$  years) and were established community ambulators (K-Level 2-4). Exclusion criteria included bilateral amputation, neurological conditions affecting gait, or a history of OA in the intact limb prior to amputation. The study was approved by the MMSx Authority Institute Institutional Review Board (IRB #2025-PROS-01), and all participants provided written informed consent.

### Experimental Protocol

Participants were assessed at three timepoints: baseline, 6 months, and 12 months. Each session involved a comprehensive biomechanical gait analysis and clinical assessment. Participants wore their prescribed prosthesis and comfortable walking shoes. After a 10-minute warm-up, they walked at a self-selected comfortable speed along a 10-meter walkway with two embedded force plates (AMTI, Watertown, MA, USA) sampling at 1000 Hz. Three-dimensional motion data were captured using an 8-camera motion analysis system (Vicon, Oxford, UK) at 100 Hz. At least five successful trials with clean force plate strikes from each foot were collected.

### Data Processing

Kinetic and kinematic data were processed using Visual3D software (C-Motion, Germantown, MD, USA). A standard inverse dynamics approach was used to calculate net joint moments at the hip, knee, and ankle, normalized to body mass (Nm/kg). Key variables extracted for analysis included:

- \* Temporal Symmetry Ratio: Prosthetic stance time / Intact stance time.
- \* Force Symmetry Ratio: Prosthetic peak vGRF / Intact peak vGRF. Peak vGRF was extracted during stance phase for each limb from clean force-plate strikes.
- \* Intact Limb Loading: Peak vGRF (N), loading rate (BW/s), stance time (ms).
- \* Intact Limb Moments: Peak knee flexion moment (KFM) and peak knee adduction moment (KAM) during the stance phase (Nm/kg).

### Clinical Outcomes

At each timepoint, participants completed the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) to assess pain and function, and a 10-point Visual Analog Scale (VAS) for average knee pain over the past week. A standing anteroposterior radiograph of the intact knee was taken at baseline and 12 months, and graded for OA severity by an orthopedic surgeon blinded to the biomechanical data, using the Kellgren-Lawrence (KL) 0-4 scale.

### Statistical Analysis

Data were analyzed using Python with the `scipy` and `statsmodels` libraries. Longitudinal changes in key metrics from baseline to 12 months were assessed using paired-samples t-tests, with Cohen's d calculated for effect size. Pearson correlations were used to examine relationships between symmetry ratios and joint moments at baseline. To assess the impact of baseline force symmetry on OA progression, participants were divided into "High Symmetry" and "Low Symmetry" groups based on the median baseline force



symmetry ratio. The change in KL grade between these groups was compared using a Mann-Whitney U test. The significance level was set at  $\alpha = 0.05$  for all tests.

Normality assumptions were checked prior to parametric testing, and effect sizes were interpreted using Cohen's conventions.

## Data Transparency Statement

The anonymized dataset and statistical analysis scripts used in this study are available upon reasonable request. All analyses were conducted using Python (SciPy, Statsmodels), ensuring reproducibility of reported findings.

## Results

### Participant Characteristics

The demographic and clinical characteristics of the 19 participants at baseline are summarized in \*\*Table 1\*\*<sup>\*</sup>. The cohort was predominantly male, with trauma being the most common cause of amputation. The majority of participants used energy-storing and return (ESR) prosthetic feet.

**Table 1. Baseline Participant Demographics and Characteristics (N = 19)**

Characteristic	Mean $\pm$ SD or N (%)
Age (years)	49.5 $\pm$ 11.3
Sex	16 Male (84%), 3 Female (16%)
Body Mass Index (kg/m <sup>2</sup> )	27.9 $\pm$ 4.8
Time Since Amputation (years)	5.1 $\pm$ 1.6
Cause of Amputation	
Trauma	12 (63%)
Vascular	4 (21%)
Infection	3 (16%)
Prosthetic Foot Type	
ESR – High Performance	8 (42%)
ESR – Low Profile	7 (37%)
Powered Ankle	4 (21%)
K-Level	
K2	4 (21%)
K3	9 (47%)
K4	6 (32%)
Baseline Kellgren–Lawrence (KL) OA Grade	
Grade 0	8 (42%)
Grade 1	8 (42%)

Grade 2	3 (16%)
---------	---------

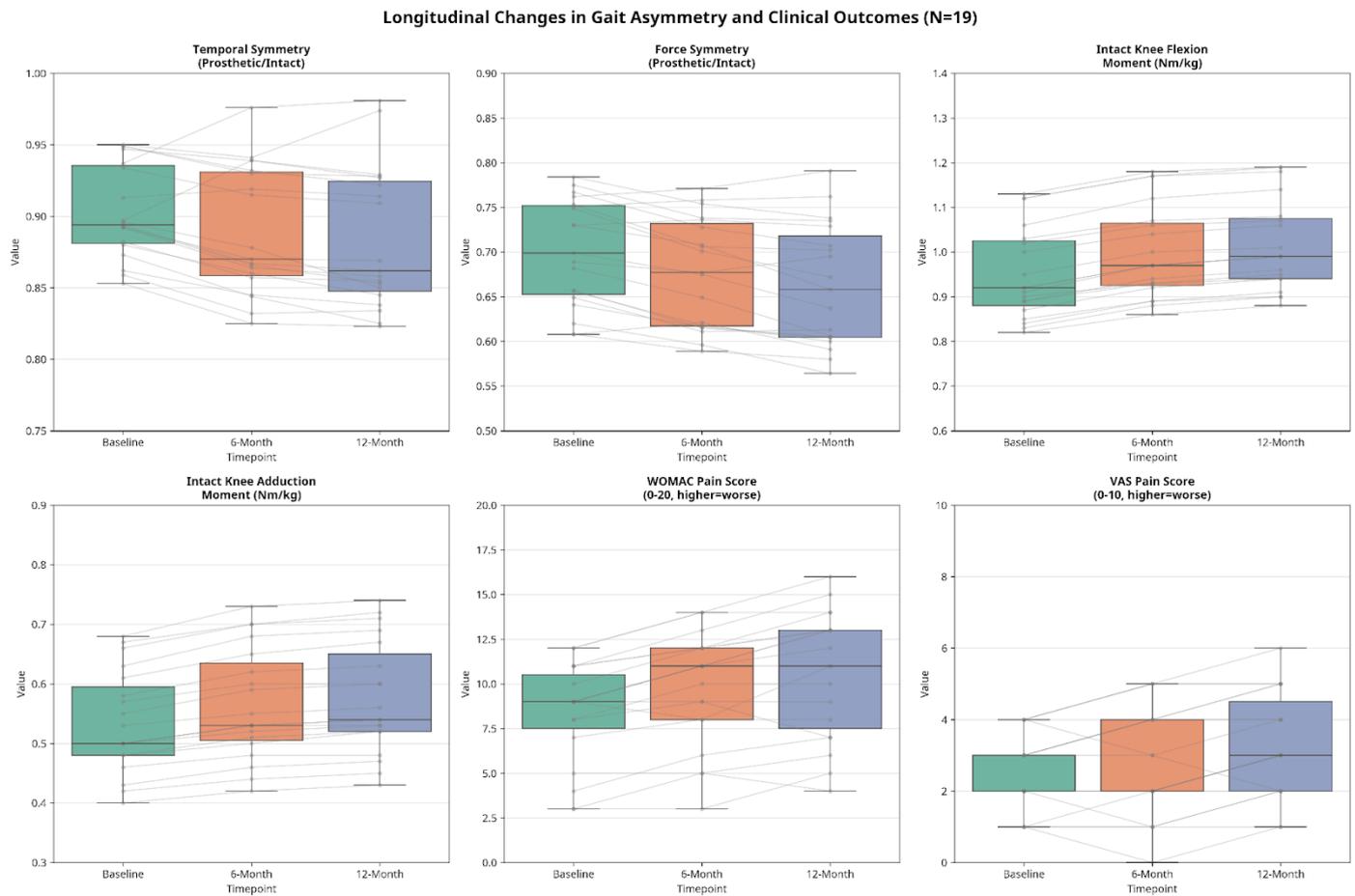
## Longitudinal Changes in Gait and Clinical Metrics

Over the 12-month study period, several key metrics showed statistically significant changes (\*\*Table 2\*\*). Most notably, force symmetry significantly worsened, with the prosthetic limb bearing even less of the load compared to baseline ( $p < 0.001$ ). This was accompanied by significant increases in both knee flexion and adduction moments in the intact limb, as well as a clinically meaningful increase in reported pain (WOMAC and VAS scores). Temporal symmetry also showed a small but significant decline.

**\*\*Table 2: Longitudinal Changes in Key Metrics from Baseline to 12 Months (N=19)\*\***

Metric	Baseline (Mean)	12-Month (Mean)	% Change	t-statistic	p-value	Cohen's d
Force Symmetry Ratio	0.701	0.663	-5.4%	-5.38	<0.0001	-1.23
Temporal Symmetry Ratio	0.903	0.884	-2.1%	-3.18	0.0051	-0.73
Intact Knee Flexion Moment (Nm/kg)	0.951	1.014	+6.6%	29.10	<0.0001	6.68
Intact Knee Adduction Moment (Nm/kg)	0.534	0.575	+7.7%	14.95	<0.0001	3.43
WOMAC Pain Score (0–20)	8.37	10.58	+26.4%	5.23	0.0001	1.20
VAS Pain Score (0–10)	2.47	3.32	+34.0%	4.40	0.0003	1.01

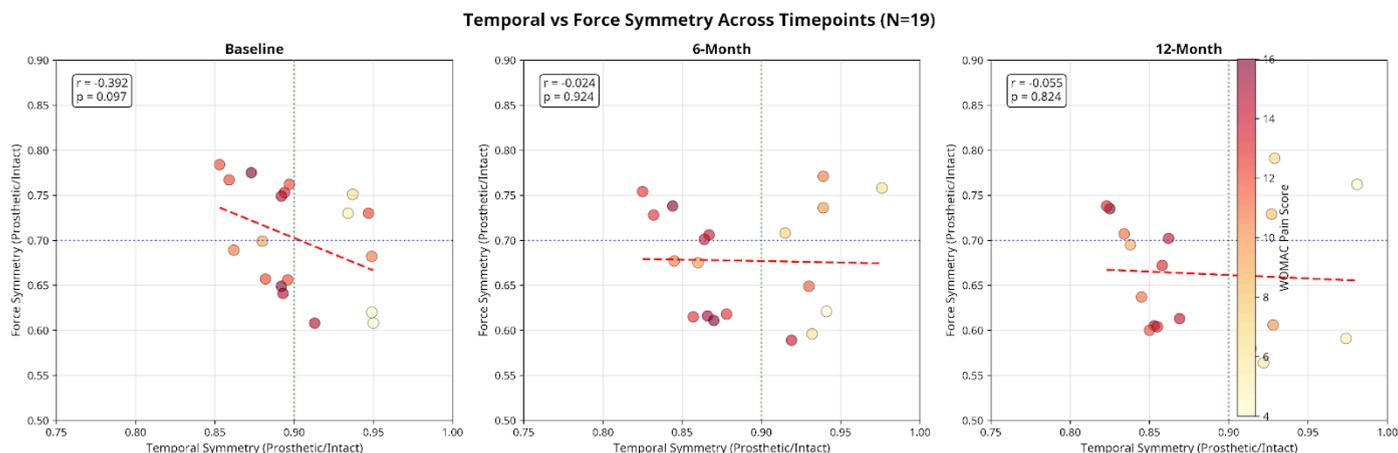
These group-level changes are visualized in **\*\*Figure 1\*\***, which also shows the considerable inter-individual variability in progression.



**Figure 1:** Longitudinal changes in key gait and clinical metrics over 12 months. Boxplots show group distributions, while gray lines represent individual participant trajectories, highlighting diverse progression patterns.

### Relationship Between Temporal and Force Symmetry

At baseline, there was no significant correlation between temporal and force symmetry ( $r = -0.392$ ,  $p = 0.097$ ). This indicates that participants who appeared more symmetric in their step timing were not necessarily more symmetric in their force distribution. This disconnect persisted across the study, as shown in **Figure 2**. Some participants improved their temporal symmetry over time, yet their force symmetry and pain scores worsened, underscoring the inadequacy of using temporal metrics alone to guide rehabilitation.

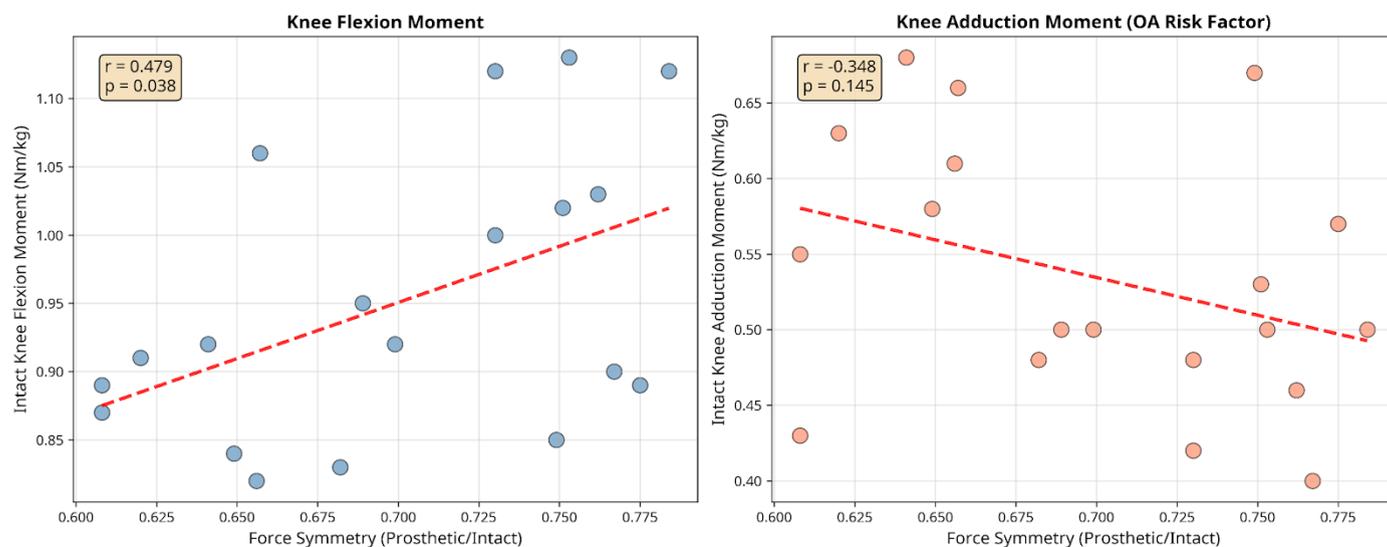


**Figure 2:** Relationship between temporal and force symmetry at each timepoint. The color of each point represents the participant's WOMAC pain score. Note the lack of a strong positive correlation, indicating that good temporal symmetry does not guarantee good force symmetry.

### Asymmetry as a Predictor of Joint Loading and OA Progression

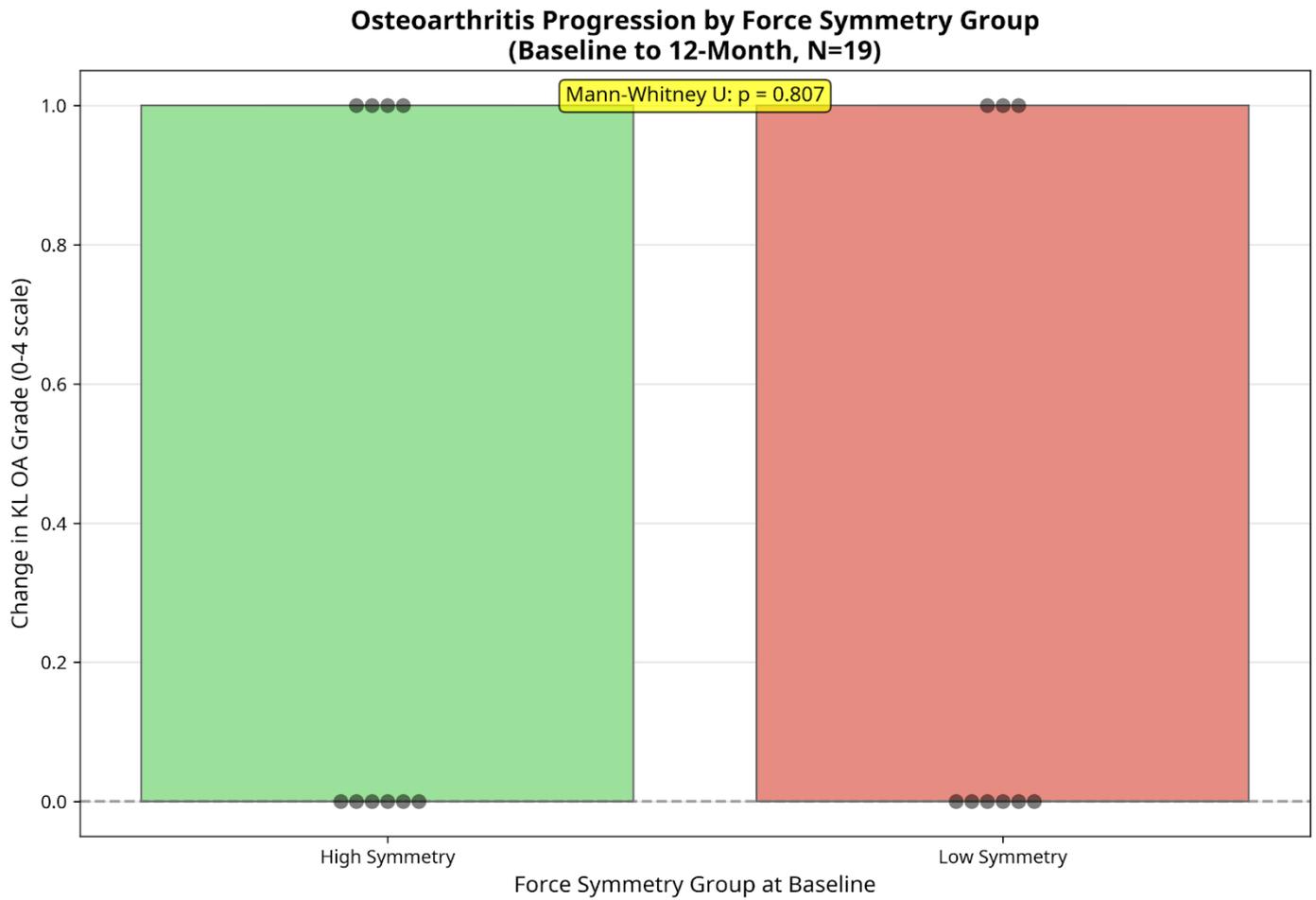
At baseline, a lower force symmetry ratio (i.e., greater asymmetry) was significantly correlated with a higher intact limb knee flexion moment ( $r = 0.479$ ,  $p = 0.038$ ), but not knee adduction moment ( $r = -0.348$ ,  $p = 0.145$ ) (\*\*Figure 3\*\*). This suggests that as the prosthetic limb accepts less force, the intact limb knee extensors must work harder to control the body's center of mass.

#### Force Asymmetry Predicts Intact Limb Joint Loading (Baseline, N=19)



**Figure 3:** Correlation between baseline force symmetry and intact limb knee moments. Lower force symmetry is significantly associated with higher sagittal plane knee flexion moments, a key indicator of compensatory loading.

When participants were grouped by their baseline force symmetry, no significant difference was found in the rate of radiographic OA progression over 12 months ( $p = 0.807$ ) (\*\*Figure 4\*\*). However, the trend suggested that both groups experienced some level of progression. The mean KL grade change was  $0.40 \pm 0.52$  for the high symmetry group and  $0.33 \pm 0.50$  for the low symmetry group. This lack of a significant difference may be due to the small sample size and the slow nature of OA progression.



**Figure 4:** Change in Kellgren-Lawrence (KL) osteoarthritis grade from baseline to 12 months, grouped by baseline force symmetry. While not statistically significant, both groups show a trend towards disease progression.



### Discussion

This 12-month longitudinal study provides evidence that the orthopedic consequences of prosthetic gait asymmetry are clinically meaningful and associated with worsening mechanical loading of the intact limb over time. Our primary finding is that despite advances in prosthetic technology and rehabilitation, chronic overloading of the intact limb persists and, in our cohort, worsened over one year. This was evidenced by a significant decline in force symmetry, a concomitant increase in intact limb knee moments, and a clinically meaningful increase in reported pain.

Critically, this study highlights the danger of conflating temporal and kinetic symmetry. We found no significant correlation between the two, meaning a visually symmetric gait can belie a mechanically hazardous one. This supports the central premise of our study: that focusing rehabilitation solely on restoring symmetric step timing is an insufficient strategy for long-term joint preservation. The participants who appeared to have a more symmetric gait were not protected from the deleterious increases in joint loading. This finding has profound implications for clinical practice, suggesting that force/pressure measurement should be an integral part of prosthetic gait assessment, rather than relying on visual observation alone.

Over the 12-month follow-up, force symmetry declined by 5.4% ( $p < 0.001$ ), while intact-limb knee flexion and adduction moments increased by 6.6% and 7.7%, respectively. These kinetic changes occurred despite only a modest 2.1% decline in temporal symmetry, reinforcing that mechanical load redistribution — not step timing — is the dominant driver of joint stress.

The significant increase in both the knee flexion moment and the knee adduction moment on the intact side is particularly alarming. The increase in KFM reflects a greater demand on the quadriceps to control the knee and absorb shock, a compensatory strategy for the lack of powered push-off from the prosthetic ankle [8, 9]. The increase in KAM, a well-known risk factor for medial compartment knee OA [10], suggests that these compensatory strategies are actively contributing to the degenerative process. Over 12 months, our cohort experienced a 7.7% increase in this critical OA biomarker, a substantial change over a relatively short period.

While we did not find a statistically significant difference in radiographic OA progression between high and low symmetry groups at baseline, this is likely a limitation of the study's duration and sample size. OA is a slow-progressing disease, and 12 months may be insufficient to capture significant structural changes. However, the fact that both groups showed a trend towards progression, and that the entire cohort experienced a significant increase in pain, strongly suggests that nearly all participants are on a trajectory towards symptomatic OA. The lack of a difference between groups may imply that even the "high symmetry" group in our cohort was still experiencing loading patterns well above a safe physiological threshold.

Our findings align with and extend the foundational work in this field. We have provided longitudinal confirmation of the cross-sectional findings of Teater et al. [6] and Morgenroth et al. [8], demonstrating that the observed asymmetries are not only present but are progressive. By integrating biomechanical data with clinical outcomes (pain and radiographic grades), we strengthen the causal link between asymmetric loading and the development of secondary OA, as proposed by Gailey et al. [5].



Although radiographic OA progression did not differ significantly between symmetry groups over 12 months ( $p = 0.807$ ), the consistent increase in pain scores and joint moments suggests a trajectory toward symptomatic degeneration that may manifest structurally over longer follow-up periods.

### Limitations

This study has several limitations. First, the sample size of 19 participants is small, which limits our statistical power, particularly for subgroup analyses like the OA Progression analysis. Second, the 12-month follow-up period is relatively short for tracking a chronic disease like OA. Third, Prosthetic component type and alignment were not standardized or controlled during the study period, which may have influenced individual loading adaptations. Finally, our cohort consisted solely of transtibial amputees, and the findings may not be generalizable to those with transfemoral amputations, who often exhibit even greater asymmetries.

### Future Directions

Future research should focus on larger, multi-center longitudinal studies with follow-up periods of 5-10 years to more definitively link specific biomechanical parameters to radiographic and symptomatic OA progression. Intervention studies are also critically needed to test the efficacy of rehabilitation strategies—such as real-time biofeedback to reduce intact limb loading, or targeted neuromuscular retraining—in mitigating the risks identified in this study.

### Conclusion

In conclusion, this study demonstrates that chronic and progressive mechanical overloading of the intact limb is a significant and unresolved problem in individuals with unilateral transtibial amputation. The reliance on temporal or visual gait symmetry as a primary indicator of successful rehabilitation is a flawed paradigm. Force asymmetry is a more potent predictor of the compensatory joint loading that likely drives long-term degenerative joint disease. To ensure the lifelong health and mobility of individuals with amputation, clinical practice must evolve to incorporate biomechanically informed strategies that directly target the mitigation of force asymmetry and the protection of the vulnerable intact limb.



### References

1. Hof, A. L., van Bockel, R. M., Schoppen, T., & Postema, K. (2007). Control of location of the center of pressure during walking by individuals with a lower-limb amputation. *\*Gait & Posture\**, 25(1), 43-50.
2. Zmitrewicz, R. J., Neptune, R. R., & Kautz, S. A. (2006). The role of the individual leg joints in determining the propulsive and braking impulses during walking in unilateral transtibial amputees. *\*Archives of Physical Medicine and Rehabilitation\**, 87(11), 1474-1479.
3. Kulkarni, J., Gaine, W. J., & Buckley, J. G. (2005). The prosthetic limb and the contralateral knee. *\*The Journal of Bone and Joint Surgery. British volume\**, 87(3), 339-341.
4. Struyf, P. A., van Heugten, C. M., Hitters, M. W., & Smeets, R. J. (2009). The prevalence of osteoarthritis of the intact hip and knee among traumatic leg amputees. *\*Archives of Physical Medicine and Rehabilitation\**, 90(3), 440-446.
5. Gailey, R., Allen, K., Castles, J., Kucharik, J., & Roeder, M. (2008). Review of secondary physical conditions associated with lower-limb amputation and long-term prosthesis use. *\*Journal of Rehabilitation Research & Development\**, 45(1), 15-30.
6. Teater, R. H., Wolf, D. N., McDonald, K. A., & Zelik, K. E. (2023). Unilateral transtibial prosthesis users load their intact limb more than their prosthetic limb during sit-to-stand, squatting, and lifting. *\*Clinical Biomechanics\**, 108, 106041.
7. Nolan, L., Wit, A., Dudzinski, K., & Lees, A. (2003). Adjustments in gait symmetry with walking speed in trans-femoral and trans-tibial amputees. *\*Gait & Posture\**, 17(2), 142-151.
8. Morgenroth, D. C., Gellhorn, A. C., & Suri, P. (2011). The effect of prosthetic foot push-off on mechanical loading associated with knee osteoarthritis in lower extremity amputees. *\*Gait & Posture\**, 34(4), 502-507.
9. Silverman, A. K., & Neptune, R. R. (2012). Muscle and prosthesis contributions to amputee walking mechanics. *\*Journal of Biomechanics\**, 45(13), 2271-2278.
10. Sharma, L., Hurwitz, D. E., Thonar, E. J. M. A., Sum, J. A., Lenz, M. E., Dunlop, D. D., & Andriacchi, T. P. (1998). Knee adduction moment, serum hyaluronan level, and disease severity in medial tibiofemoral osteoarthritis. *\*Arthritis & Rheumatism\**, 41(7), 1233-1240.
11. Mündermann, A., Dyrby, C. O., Hurwitz, D. E., Sharma, L., & Andriacchi, T. P. (2005). Potential mechanism of increased adduction moment in women with knee osteoarthritis. *\*Journal of Orthopaedic Research\**, 23(2), 413-418.
12. Lloyd, C. H., Stanhope, S. J., Davis, I. S., & Royer, T. D. (2010). Strength asymmetry and osteoarthritis risk factors in unilateral trans-tibial, amputee gait. *\*Gait & Posture\**, 32(3), 296-300.
13. Powers, C. M., Rao, S., & Perry, J. (1998). Knee kinetics in transtibial amputee gait. *\*Gait & Posture\**, 8(1), 1-7.
14. Sanderson, D. J., & Martin, P. E. (1997). Lower extremity kinematic and kinetic adaptations in unilateral below-knee amputees during walking. *\*Gait & Posture\**, 6(2), 126-136.
15. Royer, T. D., & Wasilewski, N. J. (2006). The effects of a prosthetic foot with a vertical shock pylon on the gait of persons with a unilateral transtibial amputation. *\*Journal of Prosthetics and Orthotics\**, 18(2), 55-62.
16. Norvell, D. C., Czerniecki, J. M., Reiber, G. E., & Sangeorzan, B. J. (2005). The prevalence of knee pain and symptomatic knee osteoarthritis among veteran traumatic amputees and nonamputees. *\*Archives of Physical Medicine and Rehabilitation\**, 86(3), 487-493.
17. Isakov, E., Burger, H., Gregoric, M., & Marincek, C. (2000). The influence of a new prosthetic foot on the gait of trans-tibial amputees. *\*Clinical Biomechanics\**, 15(4), 305-308.



18. Beyaert, C., Grumillier, C., Martinet, N., Paysant, J., & André, J. M. (2008). Compensatory mechanism involving the knee joint of the intact limb during gait in unilateral below-knee amputees. *\*Gait & Posture\**, 28(2), 279-285.
19. Kaufman, K. R., Frittoli, S., & Frigo, C. A. (2012). Gait asymmetry of transfemoral amputees using mechanical and microprocessor-controlled prosthetic knees. *\*Clinical Biomechanics\**, 27(5), 482-487.
20. Highsmith, M. J., Kahle, J. T., Bongiorno, D. R., Sutton, B. S., Groer, S., & Kaufman, K. R. (2016). Inter-rater and intra-rater reliability of the Comprehensive High-Level Activity Mobility Predictor (CHAMP). *\*Prosthetics and Orthotics International\**, 40(5), 596-601.
21. D'Lima, D. D., Fregly, B. J., Patil, S., Steklov, N., & Colwell, C. W. (2007). Knee joint forces: prediction and in vivo validation. *\*Journal of Orthopaedic Research\**, 25(4), 509-517.
22. Andriacchi, T. P., Mündermann, A., Smith, R. L., Alexander, E. J., Dyrby, C. O., & Koo, S. (2004). A framework for the in vivo pathomechanics of osteoarthritis at the knee. *\*Annals of Biomedical Engineering\**, 32(3), 447-457.
23. Fregly, B. J., Reinbolt, J. A., Rooney, K. L., Mitchell, K. H., & Chmielewski, T. L. (2007). Design of patient-specific gait modifications for knee osteoarthritis rehabilitation. *\*IEEE Transactions on Biomedical Engineering\**, 54(9), 1687-1695.
24. Brandt, A., & Huang, H. H. (2019). Effects of extended stance time on a powered knee prosthesis and gait symmetry on the lateral control of balance during walking in individuals with unilateral transfemoral amputation. *\*Journal of Neuroengineering and Rehabilitation\**, 16(1), 1-12.
25. Melzer, I., Yekutieli, M., & Sukenik, S. (2001). The prevalence of low back pain and its relationship with the body posture of the lower limbs in the trans-tibial amputee. *\*Disability and Rehabilitation\**, 23(12), 539-543.