

Clinical Biomechanics

Comparing prosthetic to sound limb gait mechanics during a turning task in people with transtibial amputation --Manuscript Draft--

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Corresponding Author:	Sheila Clemens, PT, MPT, PhD Lexington, KY UNITED STATES
First Author:	Sheila Clemens, PT, MPT, PhD
Order of Authors:	Sheila Clemens, PT, MPT, PhD Corey Pew
Abstract:	Background: Observational gait analysis is frequently used by clinicians to subjectively assess straight walking but is not often used to examine turning. Interlimb comparisons of phase-specific turning biomechanics in people with unilateral lower limb amputation has not previously been documented. Methods: A retrospective examination of gait kinematics and kinetics from five participants with unilateral transtibial amputation was performed. Data were collected during 90° step and spin turns capturing three distinct turning steps. Gait metrics of interest included: total turn time, stance time, peak knee flexion angle during Pre-Swing and Initial Swing gait phases, peak hip flexion and extension, ground reaction impulse, and whole body angular momentum (WBAM). Statistical comparisons were made based on turn type between sound and prosthetic limbs. Findings: During the three turn steps (approach, apex, depart), participants spent significantly more time ($P < 0.01$) on their sound limb compared to their prosthetic limb regardless of turn type. Additionally, the prosthetic limb hip and knee exhibited more flexion ($P < 0.05$) during the apex step of turns, and the sound limb exhibited higher WBAM ($P < 0.05$). Interpretation: This descriptive study offers the first phase-specific quantification of turning biomechanics in people with lower limb amputation. Results are clinically translatable and afford insight into turn negotiation in people with gait pathology. Results indicate that people with unilateral transtibial amputation overutilize their sound compared to their prosthetic limb during 90° turns, and that the prosthetic limb is performing differently than the sound limb, potentially increasing risks of injury or falls.
Suggested Reviewers:	Malaka Finco, PhD, CPO Post doc researcher malakafinco@my.unthsc.edu Prosthetist biomechanist Szu Ping Lee, PT, PhD Associate Professor, UNLV szu-ping.lee@unlv.edu Amputation rehab specialist, biomechanist

March 6, 2023

Sheila M. Clemens, PT, MPT, PhD
University of Kentucky
College of Health Sciences
Department of Physical Therapy
900 S. Limestone
Lexington, KY 40536, USA

Corey Pew, PhD
Montana State University
College of Engineering
Department of Mechanical and Industrial Engineering
112 Roberts Hall
Bozeman, MT 59717, USA

Dr. Amit Gefen
Editor-in-Chief, Clinical Biomechanics

Dear Dr. Gefen,

Thank you for your consideration of the revised manuscript titled, "Comparing prosthetic to sound limb gait mechanics during a turning task in people with transtibial amputation." I greatly appreciate the opportunity to publish, once again, in a journal as esteemed as Clinical Biomechanics, as the impact of works in Clin Biomech is international and, most importantly, interdisciplinary. Detailed edits in response to reviewer comments on our original article (transferred from Gait & Posture) have been made. We feel that the reviewers' critiques highlighted areas of weakness and have resulted in a stronger manuscript. I look forward to future communication regarding the status of the article.

All authors have made significant contributions to this article in the areas of methodology, data collection and analysis. Each of the authors has read and concurs with the content in the final manuscript. The material within has not been and will not be submitted for publication elsewhere except as an abstract. Authors report no conflicts of interest or declarations. All subjects signed Informed Consent prior to participation in this study.

Thank you again for your time and effort in consideration of this manuscript, and we look forward to hearing from you.

Sincerely,

Sheila M. Clemens, PT, MPT, PhD
Corresponding author
Email: sheila.clemens@uky.edu

Corey Pew, PhD

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Authors of all papers should submit this checklist together with their manuscript. The checklist will be made available to Editors to assist with preliminary assessment. Please refer to the Guide for Authors found at <https://www.elsevier.com/journals/clinical-biomechanics/0268-0033/guide-for-authors> before submitting your manuscript

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Basic requirements	Author response or further detail	Tick
Highlights	Avoid using abbreviations in the highlights and ensure each bullet point (between 3 & 5 required) doesn't exceed 85 characters	X
Title page	Avoid using abbreviations in the title	X
Title page	There should be no phone/fax on title page even if supplied (just the corresponding author's email address).	X
Word Count	Give word counts on the title page for both the abstract and the main text (excluding references and legends). The length should not normally exceed 4000 words with around six figures/tables (large data tables and multi-part figures are generally best placed in Supplementary Data).	X
Line numbers/Page numbers	Line numbers and page numbers need to be present in the manuscript	X
Abstract	In the Abstract, the following section headings (in italics) should each start on a new line: Background, Methods, Findings, and Interpretation. Only universally accepted and understood abbreviations are allowed in the Abstract (e.g. CT, MR), but no specialties or author-defined abbreviations (e.g. OA, osteoarthritis; TKR, total knee replacement etc). Please also ensure bullet points DO NOT appear in the abstracts. Finally, the abstract must not exceed 250 words.	X
General	Add country to all addresses	X
General	Check for incorrect and inconsistent case/italics for symbols. Ensure statistical abbreviations are in correct case and style (e.g., capital italic for P). Use n for number. SI units must be used. Conventions for abbreviations can be found in Units, Symbols and Abbreviations (available from the Royal Society of Medicine, www.rsmpress.co.uk). Confidence intervals are preferred over just P values. Please provide information on the Institutional Review Board (institute, city and country) and granted approval reference for studies in which animal or human subject data has been acquired.	X
Acronyms	Acronyms need to be defined at first use.	X
Acronyms	Acronyms with 'of' in them such as 'range of motion' should be abbreviated as RoM (not ROM)	X
Equipment info	Sources of equipment etc. should have the model of the equipment used, company, city, and country.	X
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Section heading	The section heading 'Introduction' should be used for all FLAs.	X
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We welcome the reviewers’ comments and the opportunity provided by the Editor to address each individual comment. We would like to thank the reviewers for their insight and time given to improve our manuscript. Significant changes have been made to the manuscript to reflect the reviewers’ concerns and we believe the peer-review process has dramatically improved the quality of this revised submission.	
Reviewer One Comments	Authors’ Response
Abstract: Last sentence of results: consider either 1) splitting into two sentences, 2) inserting a comma between "SO limbs" and "and," or 3) rephrasing to "...over the three steps between PRO and SO limbs, with sound limbs exhibiting higher WBAM" if this is true. Upon first read I was confused between the term "phase-specific" stated in the background and conclusion as opposed to the term "position-specific" stated in the methods. Are these the same idea?	Thank you for this comment, the sentence was restructured for improved clarity. We appreciate the reviewer’s insight and have reworded the Methods portion to reflect the comparison of inner to outer foot position between SO and PRO limbs.
Highlights: Perhaps this was intentional, but the first bullet states "kinematics" while the abstract results section states "kinematics and kinetics."	Thank you. Language was changed to the more comprehensive term “biomechanics.”
Methods: 2.1 Study Design Page 4 Lines 46-49: Could the authors add more detail regarding why 5 trials were collected with a PRO apex but only 3 trials were collected with a SO apex?	Thank you for pointing this out. The original study that collected this experimental data was only concerned with loading on the prosthesis. In addition, time limitations during data collection only allowed for 3 trials on the intact limb as the prosthetic limb was the data of interest at the time.

Could the authors provide a brief statement on how the prosthetic foot markers were placed in comparison to the sound foot? The marker placement might also be mentioned as a potential limitation of the study, particularly at the prosthetic foot. Or perhaps this is why ankle kinematics are not reported in this manuscript? Please clarify. Could the authors provide a demographic table or include a brief statement on each participant's componentry/suspension/K-level/time since amputation? 2.2 Procedures First sentence: This is the only sentence in the manuscript where "intact limb" is used instead of "sound limb." Please change to "sound limbs" for consistency or some variation of "...intact (sound) limbs." 2.3 Statistical Analysis The terms "subjects" and "participants" are used	Thank you for requesting this clarification. Markers on the foot/ankle were placed in similar positions to those on the intact limb. Kinematics on the prosthetic ankle were not reported because prosthetic hardware included a prototype transverse rotation adapter that resulted in values that were not comparable between limbs for the purposes of this work. Thank you for this suggestion. A new table has been added (Table 2) to provide demographics for the individual participants. Unfortunately, we do not have specific information regarding the suspension/K-level/Time since amputation. However, the original manuscript (which has been cited in the revised version of our manuscript) indicates the foot component: <i>A certified prosthetist fit the VSTA to each participant. The study apparatus included the VSTA and iPecs attached to their as-prescribed socket and liner with a Vari-Flex Low Profile (Ossur, Reykjavík, ISL)</i> In addition, the inclusion criteria indicate that participants were experienced prosthesis users with no use of upper limb aids who wear their prosthesis at least 8 hours each day indicating they are highly active and mobile (K3 or K4 amputees). Thank you for bringing this to our attention. Wording has been corrected in both sections 2.2 and 2.3.
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interchangeably in this paragraph. Please select one for consistency. "Subjects" is also used on the last sentence of the introduction, the last sentence of 2.1 Study Design, and the "spin turn sentence" (lines 17-18) under 2.2 Procedures.	
Results: 3.3 Coronal... Please define GRI as Ground Reaction Impulse at first mention.	This has been corrected, thank you.
Discussion/Conclusion: Excellent ties to inform clinical practice throughout the discussion (e.g., "importance of maintenance of normal hip ROM to offer optimal turning abilities", "encouraging a patient to avoid using a step turn technique with an outer symptomatic limb", etc.). I was expecting to see a brief recap of these specific clinical takeaways in the conclusion, as well.	Thank you for this compliment! Language has been adjusted in the Conclusion section to offer additional interpretation of our results to clinical practice.
References: "73" is listed between "22" and "23"	We appreciate the reviewer's observation, however the "73" listed is simply the page number continuation of citation #22.
Figures and tables: Very clear and concise tables and figures. Figure 2: Please update the legend in panel c to either "Prosthesis" and "Sound" or "PRO" and "SO"	Thank you for the kind comment. Thank you for noticing this inconsistency, the figure has been updated.

Many headings in Tables 2 and 3 are bold, which makes the significant p-values stand out less. Consider adding a * or ** system to the bold p-values for ease of reading.	Thank you for this suggestion. Updated tables 3 and 4 now have both bolded text and an asterisk.
Reviewer Two Comments	Authors Response
Highlights: The highlight should outline the key findings of the study, rather than be a very concise overview, as currently stated.	Thank you for this insight. Highlights were rewritten to better reflect the key findings of the study.
Abstract: The reference to observational gait analysis suggests non-instrumented gait analysis. The use of this term here seems inaccurate. The results should state key findings including statistical outcomes, rather than broad statements. Avoiding acronyms in the abstract would also aid accessibility.	We appreciate the reviewer's comments and would like to confirm that observational gait analysis, commonly performed by clinicians, is indeed subjective, non-instrumented gait analysis. More details were added to highlight statistical differences in our results. Furthermore, the majority of the abbreviations were spelled out to improve interpretation of the reader.
Introduction: This section is generally well written and provides a good background to the study. There seems to be some confusion in the focused aim of the study. Why is observational gait analysis important here? Has this been validated for measuring turning in this group? Why would phases of gait be related to turning tasks? Terms like engineering metrics also muddy the waters further. Maybe if authors can revisit this section and clearly state the	Thank you for this compliment. We thank the reviewer for the insightful questions and have revised the Introduction to reflect the reviewers concerns and enhance the rationale for performing our study.

relevance and purpose of the, project, which seems clear if not clearly stated, this would improve this section.	
Methods: In the study design, it is clear that instrumented gait analysis was used to collect the original data set. Please see previous comments re: observational gait analysis, to me this has caused some confusion. The processing of raw data (Vicon) to Visual 3D needs a much greater depth of description. Where participants instructed to turn in a specific fashion or were these incidental? What were their preferred strategies? There needs to be a description of the statistical procedures employed prior to the linear mixed model analysis.	We hope that the additional verbiage added to the Introduction section, and the response to previous comments, have provided clarity to the reviewer regarding non-instrumented clinical observational gait analysis and instrumented lab-based analysis. Data analysis performed in V3D was used to determine the metrics of interest as described in Table 1 Language was added about how participants performed the 90 degree turns, thank you for these questions. Thank you for this suggestion. Unfortunately, we are not clear what additional information would be helpful to the reviewer regarding the statistical analysis.
Results: The outcome measure reported here are not defined nor are the descriptions of their calculation provided in the methods section.	The authors appreciate the reviewer's comments but are unsure which "outcome measures" are being referred to. In this study, no standardized gait or rehabilitation "outcome measures" were utilized. If the reviewer is referencing the temporal-spatial parameters of interest and the positional parameters of the joints during turning, the authors would like to express that these parameters are typical variables assessed during human gait and are all clearly defined in Table 1.

When referring to normative values, are authors referring to condition-specific data? Often in this section, results are described as greater/smaller and so on but magnitudes are not reported nor statistical analyse outcomes, on a consistent basis.	Thank you for this question. A citation was previously provided for the normative values, but additional information was added for clarification. We acknowledge this language and appreciate the reviewers' comments. Due to the multiple interlimb and phase-specific comparisons, the authors felt it would be too confusing to the reader to consume every detailed difference versus having a more relative, useful overview. Table 4 and subsequent figures provide specifics and are referenced for the reader's ease of understanding and verbiage was added to highlight significant differences in data.
Discussion: Broadly speaking, the discussion provides an extensive overview of the results of the study. Thus is well written but it seems that some more insightful analyses would be useful here. Potentially, this section could be made much more concise with either clinical and/or mechanical interpretations being made more frequently. The suggestion that stance time during certain aspects of turning might lead to overuse and osteoarthritis seems like a big jump.	Thank you. Language was added to the Discussion to strengthen the clinical utility of our results and, per Reviewer 1's praises of the Discussion section, we have maintained most of the language. Substantial previous research has reported associations between gait asymmetries and arthritis formation in lower limb amputees. Some of this recent work was cited in the original manuscript to justify the statement.

Highlights:

- Biomechanical differences exist between prosthetic and sound limbs during turning
- Results suggest that participants relied on their sound limb more during turning
- Quantitative analysis of turning offers translation to clinical practice

Title: Comparing prosthetic to sound limb gait mechanics during a turning task in people with transtibial amputation.

Authors: Sheila Clemens, PT, MPT, PhD¹, Corey Pew, PhD²

Affiliations: ¹Department of Physical Therapy, College of Health Sciences, University of Kentucky, 900 S. Limestone, Lexington, KY 40536, USA

²Department of Mechanical and Industrial Engineering, Montana State University, Bozeman, MT 59717, USA

Correspondence: Sheila Clemens, Department of Physical Therapy, College of Health Sciences, University of Kentucky, 900 S. Limestone, Lexington, KY 40536. Email: sheila.clemens@uky.edu

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Abstract word count: 250

Manuscript word count: 2, 970

23 **Abstract**

24 *Background:* Observational gait analysis is frequently used by clinicians to subjectively assess
25 straight walking but is not often used to examine turning. Interlimb comparisons of phase-
26 specific turning biomechanics in people with unilateral lower limb amputation has not
27 previously been documented.

28

29 *Methods:* A retrospective examination of gait kinematics and kinetics from five participants
30 with unilateral transtibial amputation was performed. Data were collected during 90° step and
31 spin turns capturing three distinct turning steps. Gait metrics of interest included: total turn
32 time, stance time, peak knee flexion angle during Pre-Swing and Initial Swing gait phases, peak
33 hip flexion and extension, ground reaction impulse, and whole body angular momentum
34 (WBAM). Statistical comparisons were made based on turn type between sound and prosthetic
35 limbs.

36

37 *Findings:* During the three turn steps (approach, apex, depart), participants spent significantly
38 more time ($P < 0.01$) on their sound limb compared to their prosthetic limb regardless of turn
39 type. Additionally, the prosthetic limb hip and knee exhibited more flexion ($P < 0.05$) during the
40 apex step of turns, and the sound limb exhibited higher WBAM ($P < 0.05$).

41

42 *Interpretation:* This descriptive study offers the first phase-specific quantification of turning
43 biomechanics in people with lower limb amputation. Results are clinically translatable and
44 afford insight into turn negotiation in people with gait pathology. Results indicate that people

with unilateral transtibial amputation overutilize their sound compared to their prosthetic limb during 90° turns, and that the prosthetic limb is performing differently than the sound limb, potentially increasing risks of injury or falls.

Key words: Amputation, turning, gait analysis

1. Introduction

Turning is a frequent daily task requiring the ability to alter lower limb kinetic symmetry in all planes of motion while maintaining balance [1, 2]. Negotiating a turn necessitates increased motor planning and motor control beyond straight walking. In able-bodied people, the stride of the inside limb of a turn shortens [3], and more time is spent on the inside foot as the body's center of mass (CoM) is shifted toward the direction of the turn [4]. People living with gait-afflicting pathology often experience increased difficulty negotiating turns [5, 6] which can hinder daily mobility and put them at increased risk for injurious falls [7]. In people with lower limb amputation (LLA), execution of a turn can be impacted by several factors including strength and balance [8], as well as the external influences of prosthetic componentry [9]. People with unilateral LLA exhibit different turning mechanics compared to able-bodied individuals, relying more on their sound limb regardless of the direction of the turn [10]. Over time, these gait deviations may put them at increased risk for overuse injuries, falls and pain-inducing musculoskeletal asymmetries due to increased stress on the sound limb [11]. Despite the pervasive nature of turning during daily mobility, little research has been dedicated to enhancing clinically applicable turn analysis.

Comprehensive examination of gait, often performed clinically by observational gait analysis, requires knowledge of typical gait phases, and expectations of normal mechanics among the phases [12]. Observational gait analysis is utilized extensively by rehabilitation and prosthetic practitioners as a succinct means of gauging gait biomechanics in a clinical setting. Accordingly, certain gait deviations are easier to assess than others with the naked eye. In particular, the amount of knee flexion during Pre-Swing and Initial Swing phases (when "push

off" occurs) is commonly assessed by trained clinicians and gait researchers [13, 14] and may be indicative of deviations at multiple points along the closed kinetic chain. Additionally, these deviations may be reflected in temporal-spatial parameters (e.g., step length asymmetries) exhibited during walking in many patients with gait pathology. Straight walking is frequently analyzed using observational analysis yet turning is not often examined in this manner. Research rarely describes common turning tasks in terms of the phases of gait, potentially overlooking valuable specifics that offer insight into how negotiation of turns could be improved. Investigating turning in more detail may be especially impactful for populations with gait pathology, like people with LLA, and could contribute to the development of targeted therapeutic and prosthetic interventions that affect turn negotiation and, ultimately, enhance safety. The purpose of this study was two-fold: (1) to quantify clinical observational gait analysis during a 90° turn, by describing phase-specific kinematics and kinetics, making it relatable to well-known straight gait analysis and (2) to compare performance of the sound limb (SO) to the prosthetic (PRO) limb in people with a unilateral transtibial amputation. We expected that our study participants would exhibit interlimb differences in turning biomechanics when comparing within-subject, phase-specific positions of the SO to the PRO limb.

2. Methods

2.1 Study design

This descriptive study was a retrospective examination of previously collected data [9]. Five men with unilateral transtibial amputation (mean $\pm$ SD; age 53 ± 14 years) gave informed consent to participate in this study approved by the Institutional Review Board at the VA Puget Sound Healthcare System, Seattle, WA, USA. Inclusion required: (1) participants be experienced

prosthesis users (at least two years post-amputation using the prosthesis for eight hours each day); (2) no use of upper limb aids; (3) no history of falls within previous six months by self-report; (4) free of any additional neurological and physical deficits that might affect gait by self-report. Gait kinematics and kinetics were collected using a 12-camera Vicon system (Vicon, Centennial, CO), and eight embedded force plates (AMTI, Watertown, MA). Raw Vicon data was processed in Visual 3D (C-Motion Inc., Germantown, MD). All participants utilized a modified Vicon Plug-in-Gait full-body model with 65 reflective markers. Markers on the prosthesis were placed in similar positions as those on the intact limb. Kinematics of the prosthetic ankle were not reported as the hardware included a prototype rotation adapter [9] that made comparison of ankle kinematics invalid for this work. All participants wore their as-prescribed socket and liner and were fit by a certified prosthetist with a Vari-Flex Low Profile (Ossur, Reykjavík, ISL) foot to accommodate hardware for the original study.

2.2 Procedures

Participants were instructed to follow the path of the force plates and perform ninety-degree right turns. No specifics on how to turn were provided. Participants start points were adjusted, as needed, to provide both spin and step turns in prosthetic and sound limbs and elicit appropriate footfalls on the force plates.[15]. A *spin* turn results when the foot on the inside of the turn is used to make the change in direction. A *step* turn results when the outside foot is used to change direction (Fig. 1). For the purposes of this study, regardless of the type of turn performed, the step that is responsible for the primary change of direction will be termed the “apex step.” Therefore, we have defined both turn types using an approach step (step 1), an apex step (step 2), and a departure step (step 3).

Insert Figure 1 about here

This analysis of the three steps involved with a 90° turn is similar to methods utilized in prior turning research [16, 17]. Measurements with respect to the ground plane utilized a rotating coordinate system with the vertical axis perpendicular to the ground and the forward axis aligned with the anterior direction of the pelvis segment. Turn trials included five with a PRO apex and three with a SO apex for each turn type. Furthermore, five trials of straight walking over a 10-meter path were collected to allow for comparison of knee and hip joint peak angles during the turn task. Metrics used to assess turning biomechanics are shown in Table 1.

Insert Table 1 about here

2.3 Statistical analysis

Statistical analysis was conducted in Matlab (MathWorks, Natick, MA) using a linear mixed effects model with random effects for intercept and slope within individual participants with $P < 0.05$ indicating statistical significance. This model allowed pairwise comparison between limbs for each metric while accounting for individual variation between participants.

3. Results

3.1 Temporal parameters

In examining each turn type by the three turn steps (approach, apex, depart), participants spent significantly more time on their SO limb compared to their PRO limb regardless of turn type (Table 3).

Insert table 2 about here

Insert Table 3 about here

3.2 Phase-specific peak joint angles

During straight walking, our study participants exhibited peak knee and hip joint angles that aligned with established normative values in the non-amputee population [12]. During the 90° turn, both SO and PRO maximal knee joint angles slightly exceeded what was observed during Pre-Swing and Initial Swing gait phases during straight walking for all three steps during both turn types. There were minimal but statistically significant differences in both Pre-Swing and Initial Swing knee angles between the limbs (Table 4), with the PRO knee more consistently exhibiting higher knee flexion during the steps.

Insert Table 4 about here.

Overall, peak hip flexion during turning was comparable to what was exhibited during straight walking (Table 4). In the approach step of both turn types as well as the departure step of a *step* turn, the SO limb exhibited more hip flexion than the PRO limb ($P < 0.01$). Peak hip extension was less during turning compared to straight gait, with the PRO limb exhibiting significantly more hip extension during approach and departure steps ($P < 0.001$), and the SO limb demonstrating significantly more hip extension during the apex step ($P < 0.001$) during both turn types.

3.3 Coronal and Sagittal Plane Ground Reaction Impulse

Examining coronal plane ground reaction impulse (GRI) suggested that GRI was almost exclusively directed toward the center of the turn (medially) with the SO limb exhibiting higher magnitudes than the PRO limb during all steps of a *spin* turn (Fig. 2a). During a *step* turn, GRI in the coronal plane was noticeably higher during the apex compared to the *spin* turn, with the PRO limb exhibiting higher coronal GRI than the SO limb during the step (Fig. 2b).

Insert Figure 2 about here.

During approach and departure steps, sagittal plane GRI is similar in magnitude when comparing spin and step turns, with the SO limb exhibiting significantly more propulsion and braking than the PRO limb. During the apex step of both turn types, the SO limb demonstrated significantly greater propulsion than the PRO limb. However, less braking was exhibited by the SO limb during the apex of a *step* turn (Fig. 2d) while more braking was exhibited during the apex of a *spin* turn (Fig. 2c).

3.4 Whole body angular momentum

In all three planes of motion during both types of turns, the range of WBAM was significantly greater over the SO limb than the PRO limb, except in the transverse plane of a *step* turn (Fig. 3).

Insert Figure 3 about here.

4. Discussion

Turning is a pervasive aspect of daily ambulation that can pose challenges to people living with mobility deficits [7]. The purpose of this study was to develop a better understanding of the kinematics and kinetics of a 90° turn in community-ambulating people with unilateral TTA. To our knowledge, this is the first study to examine joint kinematics during common turning tasks in the LLA population using phase-specific interlimb comparisons to quantify frequently observed gait parameters. This research offers novel insight into how higher functioning individuals with unilateral TTA are negotiating common turn angles and provides a basis for further turn-related research in mobility challenged patient populations.

The observation that study participants spent more time over their SO limb during the three steps analyzed of both turn types aligns with previous LLA research [10]. The former study examined 180° turning in community ambulators with LLA, with the current study reflecting this

same turn strategy during 90° turns. This turning technique differs from what is exhibited in the non-LLA population where more time is spent over the inner limb of a turn [3] and could potentially predispose someone with unilateral LLA to undue overuse of the SO limb leading to secondary conditions like osteoarthritis [18].

Knee and hip joint angles during straight gait have been previously reported in the LLA population [19, 20]. However, examining knee and hip joint angles during turning provides novel information regarding kinematics of a commonly performed, but rarely analyzed, daily task. It is expected that peak hip flexion and extension is approximately 20° in both directions, and normal peak knee flexion during Pre-Swing is approximately 30-40° and during Initial Swing is approximately 50-60° in straight walking [12]. These normative values allow for ease in identification of gait deviations during observational gait analysis and represent gait phases where the properties of the prosthetic foot and targeted prosthetic gait training have the potential to influence gait mechanics.

Our participants exhibited peak hip joint flexion/extension values during straight walking that are comparable to previously published values in the LLA population [19]. Additionally, our participants' peak knee joint flexion during straight walking aligns with both normative values during Initial Swing and with past LLA findings where the PRO knee exhibits greater peak knee flexion than the SO limb [20]. Unique to our study is the reporting of knee flexion during the Pre-Swing phase as well, in which our participants exhibited ROM values that align with normative data.

Interlimb comparisons of peak joint angles at the knees and hips while negotiating a 90° turn have not been previously reported in any patient population. Hence, our results provide new

insight into this functional mobility task and offer foundational parameters as a resource for clinicians. Similar to straight walking, PRO limb knee flexion was greater during turning than the SO limb during both Pre- and Initial Swing phases. The increased PRO knee flexion may result from efforts to ensure clearance of the PRO toe during swing. The exception was during the approach step of the *step* turn where the SO limb exhibited greater knee flexion in both phases. Though small in magnitude, the higher SO limb knee flexion angle may serve to enhance translation of the CoM toward the PRO limb during the impending apex step and be indicative of a motor planning technique specific to people with unilateral lower limb deficits. Previous turn research using a 270° angle [4] reported higher knee flexion values of the inner limb of the turn, our *spin* turn apex step results align with this finding.

Peak hip extension is often examined during walking as it is commonly deficient during pathological gait patterns [21]. Previous 90° turning research in able-bodied individuals reported hip extension angles similar to straight walking hip angles for *step* turns but decreased for *spin* turns [22]. Our results indicate that during both types of turns, peak hip extension is less than during straight walking. Furthermore, our participants exhibited greater hip extension angles of both limbs when the SO limb was the apex regardless of the type of turn being performed. This is potentially reflected in the higher propulsive impulse exhibited by the SO limb apex step. However, this same reflection is not apparent in the PRO approach and departure steps, possibly due to a lack of propulsive properties inherent to the prosthetic foot despite achieving full hip extension. Additionally, the full hip extension of the PRO approach step could potentially indicate increased effort by the amputee in translating the CoM away from the approach step PRO limb and toward the impending SO apex step where they are more confident with balancing. Clinically,

the amount of peak hip extension exhibited by our highly functioning participants highlights the importance of maintenance of normal hip ROM to offer optimal turning abilities after LLA. Frequently, hip extension is decreased in people with LLA [23], often contributing to gait deviations. Though many of our interlimb joint angle comparisons were statistically significant, it is undetermined if these minor differences translate in a clinically meaningful way. Future research into the effects of prosthetic componentry and gait training on joint angles may provide insight into any clinical significance of the differences.

As with peak joint angles, coronal and sagittal plane GRI have not been previously reported per individual turn steps. Past work has found, generally, GRI in both coronal and sagittal planes was lower in the PRO limb compared to the SO limb during circular (360°) turning [24]. Our results are partially in contrast to previous findings as our participants exhibited higher medially directed GRI with the PRO limb versus the SO limb during *step* turns regardless of which limb provided the apex step. This may reflect an increased effort required by the PRO limb during a *step* turn to propel the CoM in the direction of the turn. Furthermore, magnitudes of coronal GRI were more evenly distributed between the three turn steps during a *spin* turn verses a *step* turn (Figure 2). This result offers possible clinical implications for training turn negotiation in people with LLA who are experiencing limb pain, which could result from prosthetic wear, or are at risk for damage to their remaining foot, as in the case of someone with diabetic neuropathy. Encouraging a patient to avoid using a *step* turn technique with an outer symptomatic limb could help mitigate forces being exerted on the limb and potentially alleviate undue stresses.

The magnitude of propulsive GRI was consistently greater with the SO limb than the PRO limb during all three steps of both types of turns, possibly reflecting the lack of push off often

considered to be a property of prosthetic foot design [25]. And as anticipated during the approach step leading into a turn, braking forces were higher in both limbs compared to propulsive forces in anticipation of a change of direction at the impending apex step. The breaking impulse differed during the apex step depending on the type of turn being negotiated. The decreased braking exhibited by the SO limb during a *step* turn may be indicative of an attempt by the SO limb at maintaining velocity of the turn to mitigate the lack of propulsion provided by the prosthetic foot during the approach and departure steps. Conversely, the increased braking of the SO limb observed during a *spin* turn may reflect the SO limb's effort to control for the higher balance demands inherent to a *spin* turn as the CoM translates over the inner foot.

Aligning with research by Nolasco et al. [26], our participants exhibited higher magnitudes of WBAM when the PRO limb was the apex of a spin turn versus a step turn. However, our study uniquely examined discrepancies in performance between SO and PRO limbs, providing novel data on WBAM during turning in people with LLA. In our study participants, the SO limb consistently exhibits higher magnitudes of WBAM in both the frontal and sagittal planes (Figure 5). These results suggest that the participants were potentially more confident over their SO limb and allowed their CoM greater latitude of movement, whereas over the PRO limb they were more guarded. This occurred during both types of turns, possibly indicating that people with unilateral LLA exhibit less desire or ability to translate the CoM over the PRO limb as indicated in other turn related research [27]. This detriment can be secondary to a multitude of factors including lack of prosthetic gait training or balance confidence properties of the prosthesis [28], pain, or a combination of potentially modifiable variables.

There are several limitations to this study, primarily that only 90° turns performed by five participants were examined in a controlled environment. However, 90° turns are one of the most common types of turns performed during the day [29] and we examined both *spin* and *step* turns providing better generalizability of the results. Furthermore, only participants with TTA were included in the study. With known differences in turn performance based on LLA level [10], our results may not be applicable to people with other levels of LLA. Additionally, because our study uniquely examined interlimb comparisons of kinetics and kinematics, our ability to compare results to previous research was limited. Lastly, many of our results exhibit statistically significant differences, however any clinical implication remains undetermined.

5. Conclusion

This study served to quantify frequently observed parameters of straight walking analysis and make them applicable to turning analysis. Turning, though pervasive in everyday mobility, has been understudied and often goes untrained in patients with LLA. The parameters presented in this study offer immediate clinical utility to practitioners who perform gait analysis, offering the opportunity for practitioners to compare observed turning performance to our data to assist in guiding therapeutic interventions like strengthening or range of motion techniques. Our results align with previous research indicating that individuals with unilateral LLA utilize their SO limb more during turning regardless of turn type. These results provide unique and fundamental data on higher-functioning community ambulating people with unilateral transtibial amputation and serve as a foundation for further turn assessment studies in populations with mobility deficits.

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Conflict of interest statement

The authors report no conflicts of interest.

Highlights:

- Biomechanical differences exist between prosthetic and sound limbs during turning
- Results suggest that participants relied on their sound limb more during turning
- Quantitative analysis of turning offers translation to clinical practice

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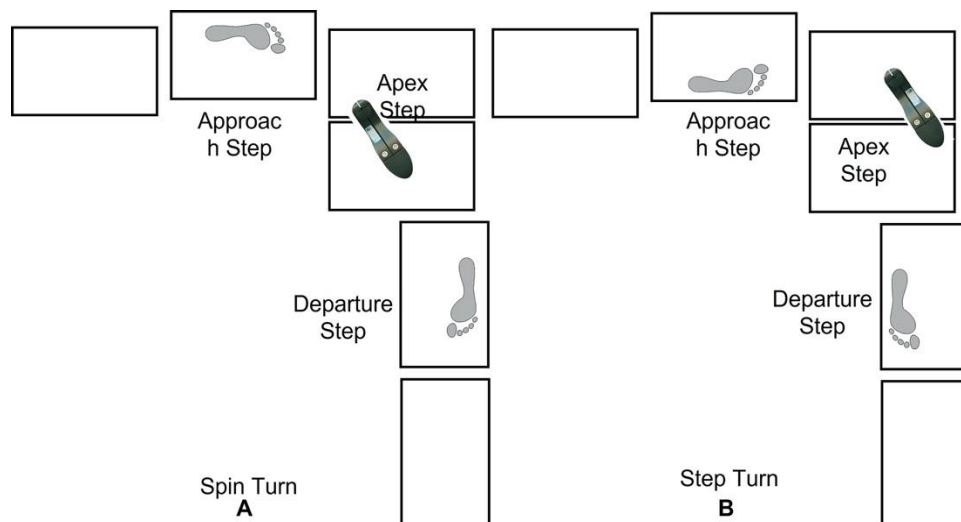
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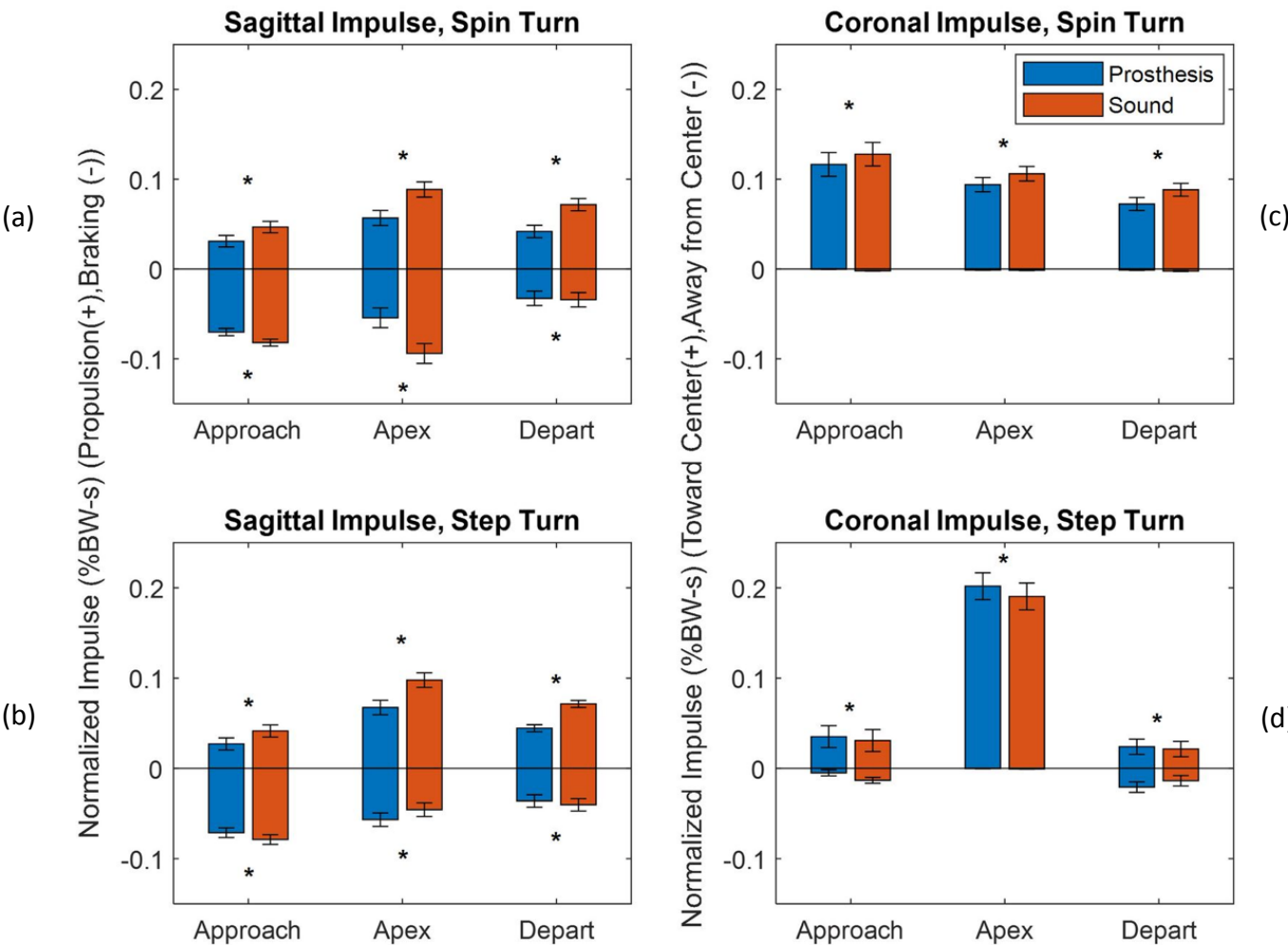
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Figure 1. Example of the two types of 90° turns, (A) spin turn, (B) step turn.

Figure 2. Interlimb comparisons of coronal plane GRI during a (a) spin turn, (b) step turn. Interlimb comparisons of frontal plane GRI during a (c) spin turn, (d) step turn. *indicates significant difference ($p \leq 0.01$), values have units %BW-s with error bars indicating $\pm$ SE.

Figure 3. Comparisons of Range of WBAM in three planes of motion. Sag=sagittal plane, Cor=coronal plane, Trz=transverse plane. Values have units of m/s with error bars showing $\pm$ SE. *indicates $p \leq 0.001$.





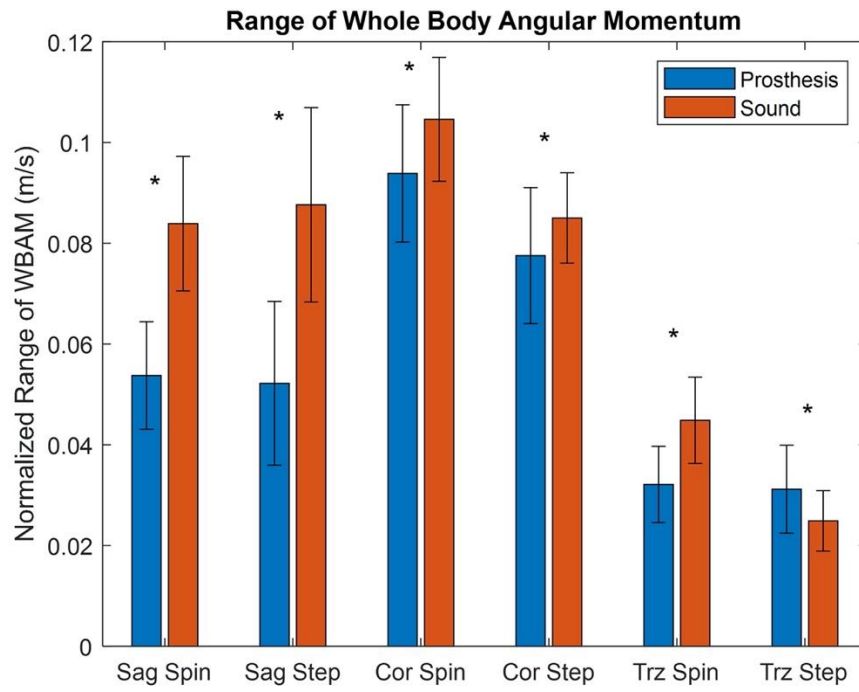


Table 1. Turning metrics of interest.

Metric	Description	Calculation	Purpose
Total Turn Time	Time for participant to move through turn	Time from heel strike of the Approach step to toe off of the Departure step	Compare performance time depending on turn type
Turn Stance Time	Time individual spends in stance on each step of the turn	Total time from heel strike to toe-off during the step of interest	Assess asymmetries in time spent on each limb
Pre-Swing Knee Angle	Knee angle at toe off [12]	Angle between the shank and thigh segments	Evaluate amount of knee flexion compared to normative straight walking values
Initial-Swing Knee Angle	Peak knee angle after toe off [12]	Angle between the shank and thigh segments	Evaluate amount of knee flexion compared to normative straight walking values
Peak Hip Flexion/Extension	Peak hip flexion/extension during each step	Angle between the thigh segment and ground reference	Evaluate amount of hip ROM compared to normative straight walking values
Ground Reaction Impulse (GRI)	Impulse in all direction	Time integral of the ground reaction forces over the gait cycle	Indicator of total limb loading
Range of Whole Body Angular Momentum (WBAM)	Range of angular momentum during a stride	The positive minus the negative peak values in the sagittal, coronal, and transverse planes over the course of a single stride (heel strike to heel strike of the limb) normalized by participant height (m) and mass (kg) [17]	Assessment of dynamic balance

Table 2. Participant characteristics.

Subject	Gender	Age	Weight (kg)	Height (m)	Amputation Side	Amputation Etiology
1	Male	35	64	1.76	Left	Traumatic
2	Male	47	85	1.77	Left	Traumatic
3	Male	66	93	1.85	Right	Traumatic
4	Male	47	98	1.89	Right	Traumatic
5	Male	69	93	1.85	Left	Traumatic

Table 3. Interlimb comparisons of temporal parameters during turn performance for total time by type of turn, and for the three steps of interest for spin turns and step turns. ‘Pros’ indicates prosthetic limb. Time is in seconds $\pm$ SE, significance ($p \leq 0.05$) is shown in **bold***.

Total Turn Time from Approach Heel Strike to Depart Heel Strike					
Spin Turn			Step Turn		
Pros apex	Sound apex	p-value	Pros apex	Sound apex	p-value
1.27 $\pm$ 0.06	1.32 $\pm$ 0.06	< 0.01*	1.22 $\pm$ 0.04	1.24 $\pm$ 0.04	p = 0.099
Turn Stance Time from Heel Strike to Toe Off of Each Turn Step					
Spin Turn					
Approach			Apex		
Pros	Sound	p-value	Pros	Sound	p-value
0.73 $\pm$ 0.03	0.77 $\pm$ 0.03	< 0.01*	0.83 $\pm$ 0.06	0.89 $\pm$ 0.03	< 0.01*
Approach			Depart		
Pros	Sound	p-value	Pros	Sound	p-value
0.75 $\pm$ 0.04	0.79 $\pm$ 0.04	< 0.01*			
Step Turn					
Approach			Apex		
Pros	Sound	p-value	Pros	Sound	p-value
0.74 $\pm$ 0.02	0.77 $\pm$ 0.02	< 0.01*	0.78 $\pm$ 0.04	0.82 $\pm$ 0.04	< 0.01*
Approach			Depart		
Pros	Sound	p-value	Pros	Sound	p-value
0.76 $\pm$ 0.03	0.81 $\pm$ 0.03	< 0.01*			

Table 4. Prosthetic and sound limb peak knee joint angle during pre-swing and initial swing and peak hip joint angle comparisons during turning and straight walking tasks. Values are angles in degrees $\pm$ SE, significance ($p \leq 0.05$) is shown in **bold***.

Pre-Swing Knee Angles								
Spin Turn								
Approach			Apex			Depart		
Pros	Sound	p-value	Pros	Sound	p-value	Pros	Sound	p-value
49.8 ± 3.8	48.7 ± 3.8	0.030*	46.6 ± 2.0	45.0 ± 2.1	0.030*	47.3 ± 3.2	46.6 ± 3.2	0.174
Step Turn								
Approach			Apex			Depart		
Pros	Sound	p-value	Pros	Sound	p-value	Pros	Sound	p-value
49.6 ± 2.6	52.1 ± 2.6	0.010*	45.1 ± 3.5	41.1 ± 3.5	< 0.001*	48.3 ± 3.1	47.4 ± 3.1	0.234
Straight walking								
Pros			Sound			p-value		
44.9 ± 1.7			42.6 ± 1.7			0.013*		
Initial Swing Knee Angles								
Spin Turn								
Approach			Apex			Depart		
Pros	Sound	p-value	Pros	Sound	p-value	Pros	Sound	p-value
65.7 ± 3.2	64.2 ± 3.2	< 0.001*	64.2 ± 1.9	63.0 ± 2.0	0.066	65.5 ± 2.9	63.6 ± 2.9	< 0.001*
Step Turn								
Approach			Apex			Depart		
Pros	Sound	p-value	Pros	Sound	p-value	Pros	Sound	p-value
61.7 ± 2.1	62.9 ± 2.1	0.068	63.5 ± 2.6	59.1 ± 2.6	< 0.001*	65.4 ± 2.8	63.9 ± 2.7	0.011*
Straight walking								
Pros			Sound			p-value		
64.8 ± 1.6			61.0 ± 1.6			0.455		
Peak Hip Flexion (+) and Extension (-)								
Spin Turn								
Approach			Apex			Depart		
Pros	Sound	p-value	Pros	Sound	p-value	Pros	Sound	p-value
23.7 ± 2.2	25.0 ± 2.2	< 0.001*	24.8 ± 1.9	24.2 ± 11.9	< 0.001*	21.7 ± 2.2	22.2 ± 2.2	< 0.001*
-12.8 ± 2.8	-11.0 ± 2.8	< 0.001*	-15.9 ± 2.5	-17.7 ± 2.5	< 0.001*	-17.1 ± 1.9	-16.2 ± 1.9	< 0.001*
Step Turn								
Approach			Apex			Depart		
Pros	Sound	p-value	Pros	Sound	p-value	Pros	Sound	p-value
22.7 ± 2.1	24.8 ± 2.1	< 0.001*	24.9 ± 2.4	22.2 ± 2.4	< 0.001*	22.5 ± 1.5	25.6 ± 1.6	< 0.001*
-11.3 ± 2.3	-9.7 ± 2.3	< 0.001*	-15.6 ± 3.3	-19.1 ± 3.3	< 0.001*	-16.6 ± 1.7	-15.5 ± 1.7	< 0.001*
Straight walking								
Pros			Sound			p-value		
25.6 ± 2.2			23.8 ± 2.2			< 0.001*		
-18.2 ± 1.8			-19.4 ± 1.8			< 0.001*		

Conflict of interest statement

The authors report no conflicts of interest.

CRediT Author Statement

Sheila Clemens: Conceptualization, investigation, formal analysis, writing-original draft, visualization. **Corey Pew:** Conceptualization, investigation, methodology, resources, data curation, writing-original draft, visualization.