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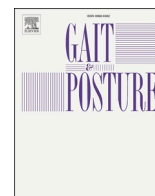
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Impact of amputation level on gait disorders in transfemoral and transtibial amputees[☆]

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ABSTRACT

Question: How does the level of lower limb amputation affect spatiotemporal gait asymmetry and cautious gait criteria to inform tailored rehabilitation interventions?

Design: A retrospective study analyzing gait patterns in individuals with unilateral lower limb amputations.

Participants: 49 amputees (22 (45 %) transtibial, 27 (55 %) transfemoral) compared to 30 healthy controls, evaluated between January 2018 and June 2023.

Intervention Participants: performed a spontaneous walking speed test on a pressure mat (Zebris® FDM 2 & 3 System, 100 Hz, v 1.18.44, GmbH, Isny, Germany) after completing rehabilitation.

Outcome Measures: Gait symmetry and cautious gait were assessed using spatio-temporal parameters, center of pressure (CoP) displacement, and foot segment forces.

Results: Increased asymmetry was observed in stance phase duration, step length, stance duration, and walking speed (95 % CI 0.398–0.658) depending on the level of amputation. Transfemoral amputees showed significant increases in step width (95 % CI 0.201–0.512), double support phase (95 % CI 0.000–0.150), and medio-lateral CoP displacement (95 % CI 0.039–0.326). The increased asymmetry in spatio-temporal parameters suggests different compensation strategies between transfemoral and transtibial levels. These differences highlight the importance of the rehabilitation paradigm in managing asymmetry and its underlying compensations during locomotor activities.

Conclusion: The level of amputation significantly impacts gait asymmetry and cautious gait parameters. Transfemoral amputees exhibit more pronounced cautious gait characteristics, likely due to the need for greater stabilization. These findings underscore the importance of personalized rehabilitation to address specific compensations and gait abnormalities based on amputation level.

1. Introduction

Amputation of a limb segment affects movement control abilities even in individuals fitted with a prosthesis. The primary goal remains consistent across all populations, but strategies vary depending on the level of amputation. Indeed, gait patterns post-lower limb amputation are impacted by the absence of sensory information from the amputated

segments [1]. Generally, gait in individuals with acquired or congenital motor impairments is characterized by asymmetry in the same parameters [2]. Conversely, gait in asymptomatic individuals is characterized by symmetry or very slight asymmetry in the spatio-temporal parameters of the gait cycle and joint kinematics [3].

Several studies have characterized gait in transtibial [4,5] and transfemoral amputees [1,6–11] as asymmetric. The characterization of

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this asymmetry through the quantification of center of pressure (CoP) trajectory during stance is a parameter already studied for both normal [12] and pathological gait [13], especially in transfemoral amputees [1, 9,10,14,15].

Transfemoral amputees exhibit shorter and wider steps compared to transtibial amputees, reflecting an increased need for lateral stability at the expense of energy efficiency, along with marked temporal asymmetry between the prosthetic and sound sides, unlike transtibial (TT) amputees who demonstrate better symmetry [16,17]. These studies agree on the temporal asymmetry between the prosthetic and contralateral limbs. They note that individuals with static balance control issues walk with a wider step. A cautious gait, as defined by Murray et al. [18] in a population of older adults, is characterized by reduced stride length, decreased walking speed, and increased stance width. This gait pattern is also observed in individuals with lower limb amputations, as a compensatory mechanism to manage balance impairments and influenced by the type of prosthesis utilized [25]. These factors contribute to an increased risk of falls in this population [19]. This mechanism reflects a slower, more deliberate walking pattern designed to minimize the risk of falls. It is an adaptive response to challenging terrains and environmental conditions, as well as to the muscular weaknesses and loss of proprioceptive feedback associated with the use of a prosthetic limb. However, to date, few studies have examined the impact of the level of amputation on these two components and their relevance in the rehabilitative care of amputees.

In this context, it is novel to evaluate spatiotemporal parameters of asymmetry and cautious gait with the aim of understanding their impact on rehabilitative care. This approach offers the potential to optimize intervention strategies, improve prosthetic component selection, and enhance monitoring for transfemoral (TF) and TT amputees, particularly given their specific challenges such as wider step width and temporal asymmetries [16,17,20]. Moreover, implementing a rehabilitation program targeted at reducing fall risk, based on parameters such as gait asymmetries and step variability, can significantly improve stability and functional outcomes for these amputees [16,20]. In recent years, prosthetic gait rehabilitation protocols have evolved due to the advent and ease of integration of technologies such as immersive reality and serious games, allowing for personalized progression in both intensity (game difficulty level, etc.) and quality (range of motion, step length). Despite these advancements, which offer new rehabilitation possibilities for patients, rehabilitation paradigms, such as gait symmetry, remain a topic of debate. Indeed, although this asymmetry is demonstrated, its integration into rehabilitation programs remains debated, particularly regarding the necessity to develop compensations for achieving symmetry or to enhance the adaptation capabilities of acquired asymmetry. According to Schmid et al. [1], the goal of gait rehabilitation in transfemoral patients is to restore step symmetry. Conversely, Hof et al. [10] and Hak et al. [21] argue, within transtibial and transfemoral population, that such asymmetry is not a gait defect but rather an adaptation to unilateral impairment. For these authors [10,21], rehabilitation should not aim to improve temporal symmetry in all patients with asymmetric impairments.

In the context of developing personalized rehabilitation and given that these paradigms offer different approaches to amputee rehabilitation, quantifying gait asymmetry and monitoring it throughout the rehabilitation process is essential. Our study contributes to this clinical community effort by aiming to identify the impact of the level of amputation on the asymmetry of spatiotemporal gait parameters.

This study aims to quantify the impact of amputation level on spatiotemporal gait asymmetry and cautious gait criteria in the context of tailoring rehabilitation interventions for individuals with lower limb amputations. The hypothesis is that the transfemoral amputee group will exhibit greater alterations in these parameters compared to the transtibial amputee group.

2. Method

2.1. Design

This retrospective, single-center study was conducted using data from the rehabilitation hospital database at the University Hospital of xxxxxx (xxxxxx, xxxxxx), covering the period from January 2018 to June 2023.

2.2. Participants

The study focused on gait analysis examinations of patients hospitalized for lower limb amputation. To be included, patients had to (i) walk without technical assistance with a unilateral transtibial or transfemoral amputation, and (ii) be capable of walking at least 20 m, corresponding to a back-and-forth walk on a track equipped with baropodometric platforms. A total of 30 able body (AB) and 49 amputees were included: 22 (45 %) transtibial and 27 (55 %) transfemoral. Approval was granted by our Institutional Review Board which provides an ethical opinion and a commitment to compliance within the framework of the MR004 methodologies (ClinicalTrials.gov ID NCT05803317). In accordance with the Declaration of Helsinki, all participants provided written consent for participation. In this retrospective study, a formal sample size calculation was not conducted due to the study design. However, this aspect was addressed by calculating effect sizes (η^2) and their 95 % confidence intervals for each variable. These calculations demonstrate that the number of subjects included in the study is sufficient to detect significant differences where they exist. The use of effect size metrics ensures the robustness of the analysis and supports the reliability of the study's conclusions, even in the absence of a priori sample size estimation.

2.3. Intervention and outcome measures

Patients were systematically evaluated before hospital discharge, following rehabilitation, and prosthetic fitting. Gait analysis was performed on a 15-meter walking track equipped with two Zebris® FDM 2 & 3 System platforms (100 Hz, Zebris Medical GmbH, Isny, Germany), allowing the measurement of support parameters over 5 m. Participants completed two consecutive 10-meter walk tests (10MWT) [22]. The database of asymptomatic participants from the movement analysis laboratory, consisting of individuals who completed five consecutive 10-meter walks at spontaneous speed.

Demographic data collected included age, weight, height, sex, amputation level (TT: transtibial or TF: transfemoral), amputation side, cause of amputation, and prosthesis details (foot class for TT, knee type and foot class for TF) [Table 1]. After excluding incomplete cycles, 10 cycles (5 right and left) per participant were analyzed. Spatio-temporal variables were calculated to describe cautious gait criteria (double support phase duration, step width, walking speed) [18,23] and symmetry parameters (gait asymmetry).

The study focused on spatio-temporal parameters and gaitogram characteristics to quantify gait cycle asymmetry and center of pressure (CoP) displacement between the prosthetic and non-prosthetic limbs [1, 9,10] [Fig. 1].

2.4. Data analysis

Differences between participant groups were assessed using one-way ANOVA, and significant differences (p -value < 0.05) were further explored with post-hoc multiple comparisons.

ANCOVAs were conducted to assess the effect of amputation level on:

(i) Cautious gait criteria, including spatio-temporal parameters (step length, stance time, cadence, phase ratios of the gait cycle) and gaitogram parameters (mean and variability of CoP width). Spatiotemporal data and CoP movements were determined based on pressure locations

Table 1

Demographic Data. AB: asymptomatic participants, TT: Trans Tibial, TF: Trans Femoral; Foot Categories: Class 1: C1, Class 2: C2, Class 3: C3; Knee Categories: M: Mechanical; H: Hydraulic; P: Pneumatic; Knee Axis: M: Monocentric; P: Polycentric; CPU: Microprocessor.

	AB = 30	TT = 22	TF = 27	Overall effect		
				p-value	F	η ² (CI 95 %)
Gender (Male/Female)	16/14	21/1	19/8			
Age (years)	32 (11)	50 (13)^a	49 (16)^b	< .001	14.550	0.277 (0.113)
Height (cm)	172.0 (9.4)	176.9 (6.3)^{a, c}	171.2 (8.5)	0.044	3.271	0.079 (0.000)
Weight (kg)	68.1 (14.4)	83.1 (19.3)^{a, c}	71.6 (17.3)	0.010	5.470	0.126 (0.013)
Side (R/L)	NA	9/13	15/12			0.263
Cause of amputation (traumatic/vascular)	NA	12/10	11/16			
Foot Class	NA	C1: 3; C2:0; C3:19	C1: 3; C2: 7; C3: 17			
Knee Class	NA	NA	M:11; H:25; P:2			
Knee Axe	NA	NA	M:12; P:4; CPU:11			
Gait Speed (m/s)	1.38 (0.13)	0.93 (0.22)^a	0.95 (0.23)^b	< .001	46.700	0.551 (0.398)

Bold value: significant effect of group with ANCOVA (p < .05)

^a Significant difference between AB and TT (p < .05)

^b Significant difference between AB and TF (p < .05)

^c Significant difference between TT and TF (p < .05)

and intensities on a force platform composed of 22,528 sensors. Zebris software calculated cadence, step duration and length, and the percentage of the gait cycle [24,25].

(ii) Asymmetry criteria, including gait asymmetry parameters (step length, stance phase and single stance phase, stance time, and walking speed) and gaitogram parameters (mean and variability of intersection, mean, minimum, and maximum CoP displacement) [15]. The asymmetry ratio was calculated according to established [Eq. 1] [26]:

$$Ratio = 100 * \frac{(val_{prosthesis} - val_{contralateral})}{0.5(val_{prosthesis} + val_{contralateral})} \quad (1)$$

(iii) The Ground Force Reaction (GRF) contributions on foot segments during the gait cycle were calculated as the ratio of the areas under the curve for different foot segments relative to the total vertical force. These calculations were performed using the trapezoidal method implemented in Matlab 2023b.

Significant differences in age and spontaneous walking speed between groups were accounted for in the ANCOVAs as continuous covariates. Assumptions of residual normality and variance homogeneity were evaluated using the Shapiro-Wilk and Levene’s tests. If ANCOVA indicated significant differences, a post-hoc analysis with Bonferroni correction was applied. In cases where variance homogeneity was not confirmed, a Games-Howell adjustment was used. For non-normally distributed data, a non-parametric Kruskal-Wallis test was conducted, followed by a post-hoc analysis with Dunn’s correction if significant

differences were detected.

3. Results

The comparison of the three groups (TT, TF, AB) shows a significant age difference, with higher ages in the amputee groups (TT=50 (13) years and TF= 49 (16) years) compared to the AB group (32 (11) years) [Table 1]. No significant differences were found in cadence and gait cycle duration between the AB group and the TT and TF groups [Table 2, Tables 1–3]

3.1. Cautious gait criteria

Significant differences were observed in step width between the TF, TT, and AB groups. The TF group showed the highest values, followed by the TT group, with the AB group having the lowest values [Table 2].

There were significant differences in the proportion of double support phases (F=3.478, p = 0.036) and walking speed (F=46.700, p < 0.001) between the three groups. The AB group demonstrated a lower double support phase and higher walking speed compared to both the TT and TF groups [Tables 1–2].

3.2. Asymmetry criteria

For gait cycle parameters, significant asymmetry was observed in the stance phase among the three groups, particularly in the single stance phase (F=28.993, p < 0.001). This asymmetry was significant between AB, TT and TF, with an increased stance phase on the contralateral side. Significant step length asymmetry was also observed in the TF group compared to the TT group (F=7.640, p < 0.001) [Table 2].

Step duration asymmetry (F = 51.166, p < 0.001) was observed among AB, TT, and TF groups, with greater asymmetry noted at higher amputation levels. Regarding speed, asymmetry increased with amputation level (F = 4.331, p = 0.017) between the TT and TF groups compared to the AB group [Table 2]. [Fig. 2] [Table 3]

3.3. CoP variables

There was a significant shift in the mean CoP M/L position (F = 9.342, p < 0.001) towards the contralateral limb in the TF group compared to the TT and AB groups, indicating reduced support from the prosthetic limb with more proximal amputation. A significant shift towards the prosthetic limb in the CoP M/L intersection location was also noted (F = 4.569, p = 0.019) in the TF group compared to the TT and AB groups.

A significant increase in the mediolateral variability of the mean CoP was observed (F = 9.630, p = 0.005) for the TF and TT groups compared to the AB group. No difference was observed in the anteroposterior variability of the mean and intersection CoP displacement.

A significant posterior shift in the minimal CoP position on the prosthetic side (F = 16.586, p < 0.001) was found between the TF group and the TT and AB groups, indicating a posterior heel strike for the TF group. Additionally, a significant posterior shift in the maximal CoP position on the contralateral side (F = 3.584, p = 0.033) was noted between the TF and TT groups compared to the AB group.

A significant increase in the mediolateral (F = 22.258, p < 0.001) and anteroposterior (F = 21.669, p < 0.001) variability of the heel strike on the contralateral limb for the TT and TF groups compared to the AB group, with greater mediolateral variability in the TF group. Lastly, a significant increase in the anteroposterior variability of the maximal CoP on the contralateral side (F = 12.349, p = 0.002) was observed for the TF and TT groups compared to the AB group.

3.4. Foot segments contribution during gait cycle

The results show a significant effect of the level of amputation on the

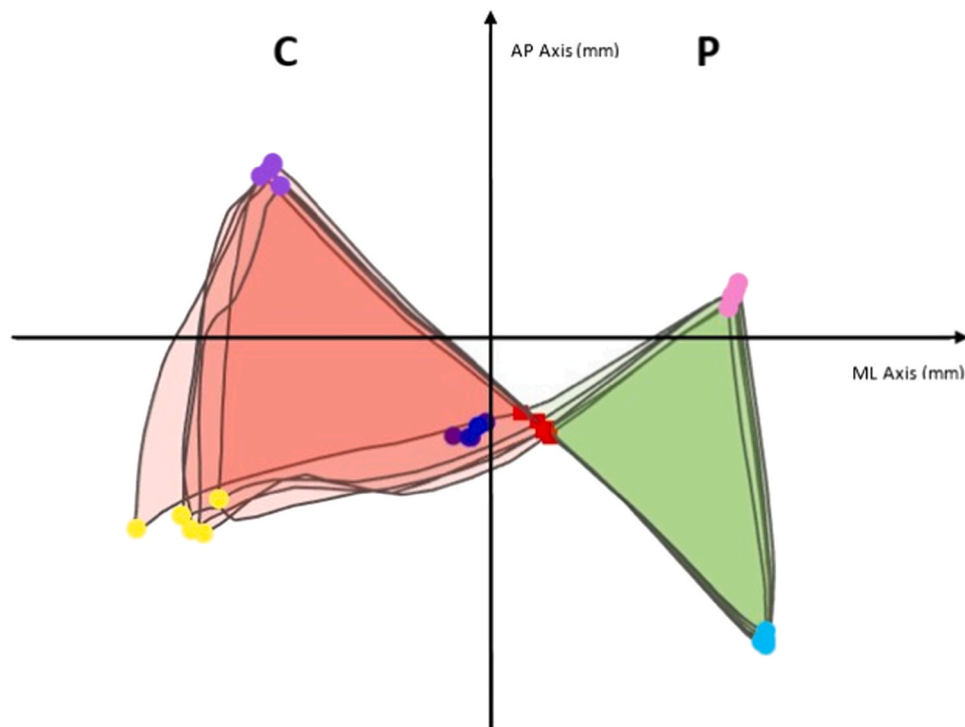


Fig. 1. Schematic representation of a gaitogram obtained via the distribution of forces measured on the force distribution measurement platform (FDP). Red squares represent the intersection of the center of pressure displacement. Blue points indicate the centroid of each gait cycle. The letters P and C, respectively indicate the prosthetic and contralateral sides. Black arrows represent the antero-posterior axis (AP) and medio-lateral axis (ML). The extremums of the gaitogram represent for each cycle: the minimum on the prosthetic side (cyan), the maximum on the prosthetic side (pink), the minimum on the contralateral side (yellow), and the maximum on the contralateral side (purple).

Table 2

Gait parameters. P: Prosthetic side, C: Contralateral Side, Asym: Asymmetric ratio between the prosthetic and the contralateral side.

Variables	AB	TT	TF	Overall effect		
				p-value	F	η^2 (CI 95 %)
Step Length P (cm)	75.0 (5.6)	58.1 (8.8)	61.4 (9.2)	0.056	2.989	0.021 (0.000 – 0.107)
Step Length C (cm)	74.4 (6.1)	59.7 (8.9)^a	57.4 (11.8)^b	< .001	37.618	0.469 (0.336 – 0.623)
Stride Length (cm)	149.3 (11.3)	117.8 (16.7)	118.8 (19.8)	0.474	0.754	0.004 (0.000 – 0.050)
Step Width (cm)	10.9 (2.5)	17.3 (4.6)^a	20.6 (3.3)^{b, c}	< .001	22.779	0.375 (0.201 – 0.512)
Stance Phase P (%)	63.7 (1.1)	64.3 (2.7)	60.5 (3.5)^{b, c}	< .001	23.484	0.365 (0.191 – 0.504)
Stance Phase C (%)	63.5 (0.9)	69.1 (3.6)^a	71.2 (3.8)^b	< .001	12.501	0.145 (0.020 – 0.287)
Single Support Phase P (%)	36.6 (1.0)	31.0 (3.6)^a	28.8 (3.8)^b	< .001	49.246	0.622 (0.537 – 0.717)
Single Support Phase C (%)	36.2 (0.2)	35.6 (2.7)	39.5 (3.6)^{b, c}	< .001	18.469	0.217 (0.040 – 0.431)
Double Support Phase (%)	27.2 (2.0)	33.4 (4.1)^a	31.7 (5.6)^b	0.036	3.478	0.043 (0.000 – 0.150)
Step Time P (s)	0.54 (0.03)	0.67 (0.10)^{a, c}	0.71 (0.12)^b	0.012	4.742	0.048 (0.000 – 0.158)
Step Time C (%)	0.55 (0.03)	0.64 (0.10)^{a, c}	0.58 (0.07)	< .001	17.189	0.200 (0.074 – 0.362)
Stride Time (s)	1.09 (0.06)	1.31 (0.18)	1.29 (0.18)	0.576	0.556	0.005 (0.000 – 0.054)
Cadence (steps/min)	110.5 (5.7)	93.7 (11.9)	94.6 (9.0)	0.957	0.044	0.000 (0.000 – 0.000)
Asym step length (%)	0.8 (3.4)	–2.7 (10.2)	7.7 (12.9)^{b, c}	< .001	7.640	0.166 (0.032 – 0.311)
Asym stance phase (%)	0.5 (1.3)	–7.0 (7.3) ^a	–16.4 (7.1) ^{b, c}	< .001	28.993	0.419 (0.246 – 0.550)
Asym single stance phase (%)	1.0 (2.3)	–14.3 (14.3) ^a	–31.7 (14.7) ^{b, c}	< .001	24.965	0.360 (0.186 – 0.499)
Asym step time (%)	–0.7 (2.0)	5.5 (9.6)^a	20.6 (12.2)^{b, c}	< .001	51.166	0.647 (0.567 – 0.760)
Asym gait speed (%)	1.5 (3.6)	–8.1 (13.2) ^a	–12.3 (15.2) ^b	0.017	4.331	0.103 (0.003 – 0.237)

Bold value: significant effect of group with ANCOVA ($p < .05$)

^a Significant difference between AB and TT ($p < .05$)

^b Significant difference between AB and TF ($p < .05$)

^c Significant difference between TT and TF ($p < .05$)

foot segments contribution (area under the curve ratio) with increase in the midfoot contribution to the GRF for the TT group (28.2 % (10.2)) compared to the TF group (19.9 % (7.4)) ($F=7173, p = 0.001$), associated with a reduction in forefoot contribution (44.8 % (9.4)) for the TT group and (52.8 % (10.5)) for the TF group ($F=8.251, p < 0.001$). There are no significant differences with AB group with 20.8 % (4.6) and 51.8 % (4.8) for midfoot and forefoot contribution respectively [Fig. 3].

4. Discussion

This study contributes to rehabilitation sciences by examining how amputation level affects cautious walking and gait asymmetry. It found that step width increases with the level of amputation, a feature often associated with cautious gait, and highlighted differences in walking symmetry between amputated and non-amputated groups. Greater

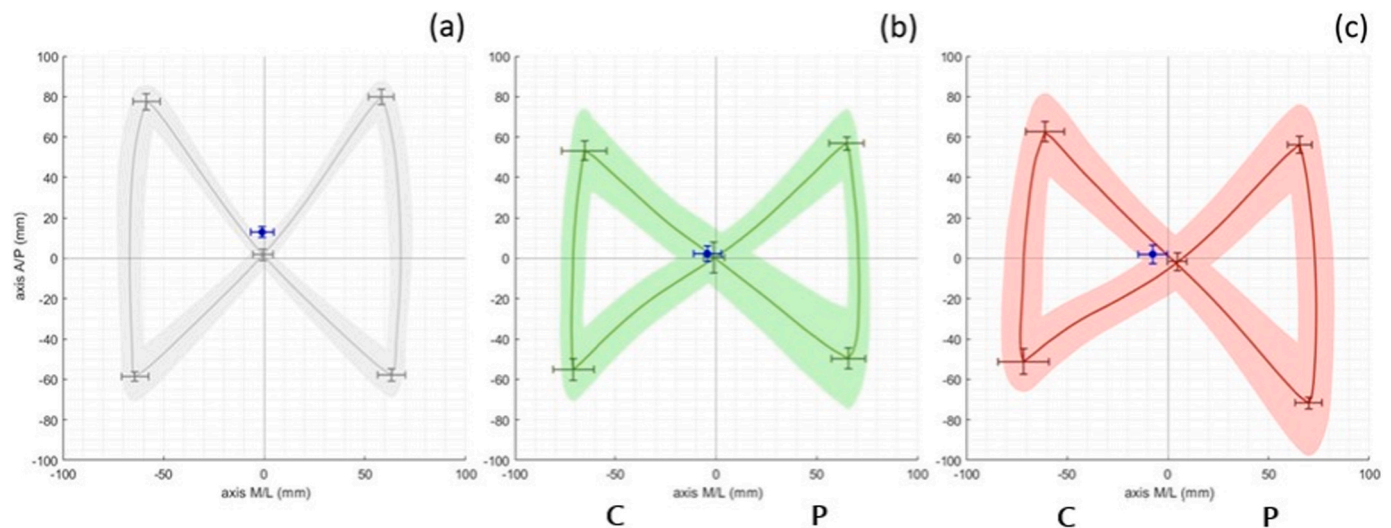


Fig. 2. Mean gaitograms of the three populations. AB (a), TT (b), TF (c) with error bars representing the inter-individual standard deviation. The centroid of each gaitogram is represented by a blue point. The intra-individual standard deviation is depicted by error bars on the medio-lateral and antero-posterior axes for the following data: centroid, COP intersection, minimum and maximum COP on the prosthetic (P) and contralateral (C) sides.

Table 3

CoP Parameters. P: Prosthetic side, C: Contralateral Side, A/P: Antero/Posterior axis, M/L: Medio/Lateral axis.

Variables	AB	TT	TF	Overall effect		
				p-value	F	η^2 (CI 95 %)
CoP Mean M/L (mm)	-0.9 (1.8)	-3.4 (3.0) ^a	-7.7 (5.9) ^{b, c}	< .001	9.342	0.179 (0.039 – 0.326)
CoP Mean A/P (mm)	12.9 (8.9)	3.5 (14.6)	1.1 (14.7)	0.659	0.419	0.010 (0.000 – 0.076)
CoP Cross M/L (mm)	-0.6 (2.4)	0.5 (13.5)	3.7 (7.4) ^{a, c}	0.019	4.569	0.100 (0.002 – 0.233)
CoP Cross A/P (mm)	1.8 (5.4)	1.9 (12.4)	-3.0 (10.9)	0.138	2.033	0.050 (0.000 – 0.160)
Min CoP P (mm)	-57.7 (11.4)	-46.0 (30.1)	-75.4 (18.0) ^{a, c}	< .001	16.586	0.283 (0.116 – 0.429)
Min CoP C (mm)	-58.6 (12.6)	-54.9 (15.6)	-51.1 (15.6)	0.523	0.655	0.016 (0.000 – 0.095)
Max CoP P (mm)	79.8 (8.3)	57.6 (17.5)	55.5 (20.4)	0.423	0.870	0.019 (0.000 – 0.100)
Max CoP C (mm)	77.5 (8.7)	53.7 (21.0) ^a	62.5 (19.9) ^b	0.033	3.584	0.054 (0.000 – 0.167)
Std CoP Mean M/L (mm)	2.7 (1.2)	3.8 (2.0) ^a	4.6 (3.2) ^b	0.005	9.630	0.102 (0.008 – 0.274)
Std CoP Mean A/P (mm)	5.6 (2.6)	6.8 (3.4)	7.2 (3.5)	0.917	0.087	0.002 (0.000 – 0.031)
Std CoP Cross M/L (mm)	2.7 (1.2)	4.9 (3.4) ^a	4.3 (3.7)	0.021	7.704	0.077 (0.000 – 0.258)
Std CoP Cross A/P (mm)	4.9 (2.1)	5.2 (2.0)	4.7 (2.4) ^c	0.040	3.354	0.073 (0.000 – 0.197)
Std CoP Min P M/L (mm)	3.0 (1.5)	5.4 (4.0) ^{a, c}	2.4 (1.0)	0.007	9.829	0.103 (0.000 – 0.330)
Std CoP Min C M/L (mm)	2.2 (1.1)	3.9 (2.5) ^a	5.4 (2.6) ^{b, c}	< .001	22.258	0.274 (0.144 – 0.431)
Std CoP Min P A/P (mm)	6.9 (2.1)	8.2 (4.7)	6.9 (3.2)	0.321	1.153	0.029 (0.000 – 0.122)
Std CoP Min C A/P (mm)	6.7 (2.5)	10.4 (5.3) ^a	12.6 (5.4) ^b	< .001	21.669	0.259 (0.102 – 0.450)
Std CoP Max P M/L (mm)	3.9 (2.0)	3.1 (2.2)	3.2 (1.9)	0.135	3.998	0.027 (0.000 – 0.205)
Std CoP Max C M/L (mm)	3.4 (1.6)	4.9 (2.8)	4.9 (2.2)	0.351	1.064	0.028 (0.000 – 0.121)
Std CoP Max P A/P (mm)	6.3 (3.0)	8.3 (4.8)	6.1 (3.0)	0.227	2.969	0.013 (0.000 – 0.147)
Std CoP Max C A/P (mm)	5.8 (2.4)	11.3 (7.4) ^a	9.6 (5.7) ^b	0.002	12.349	0.138 (0.031 – 0.339)

Bold value: significant effect of group with ANCOVA ($p < .05$)

^a Significant difference between AB and TT ($p < .05$)

^b Significant difference between AB and TF ($p < .05$)

^c Significant difference between TT and TF ($p < .05$)

asymmetry in gait cycle duration correlates with higher amputation levels. These compensatory strategies between TF and TT amputation levels are influenced by the segments lost and their impact on safety. TF amputees often prefer heel strike for knee stability, despite its lower stability compared to midfoot strike. These strategies reflect the balance between security and mobility. Understanding gait patterns by amputation level is crucial for personalized rehabilitation, distinguishing between compensatory mechanisms and actual gait abnormalities.

Our findings align with previous studies [1,10,27] showing increased step width in amputees, particularly in the TF group. Schmid et al. [1] attribute this to the loss of sensory information, affecting prosthetic foot placement at heel strike, while Hof et al. [10] suggest lateral foot placement enhances safety. Our results are consistent with studies [1, 28–30] reporting increased double support phase, though interpretations vary. Isakok et al. [28] link this to reduced prosthetic foot

mobility in transtibial amputees, while Hof et al. [10] and Schmid et al. [1] point to prosthetic knee stability issues. Despite these factors, our study finds no significant differences between TF and TT groups, indicating both adopt cautious walking strategies. This caution is related to careful weight transfer onto the prosthetic limb [29]. The prolonged double support phase is influenced by multiple factors, including heel strike and prosthetic limb stance phases [1]. If the prosthetic knee is not fully extended, it can cause instability and delay push-off from the contralateral foot, extending the double support phase for perceived safety [1]. [8,17,28]

Our results reveal a significant difference in support phase duration, favoring the contralateral limb, consistent with previous studies on TF amputees [10,27,31]. This longer support phase on the contralateral side may result from better propulsion and balance control, increasing amputee's confidence in their intact limb [1]. Vanicek et al. [32] found

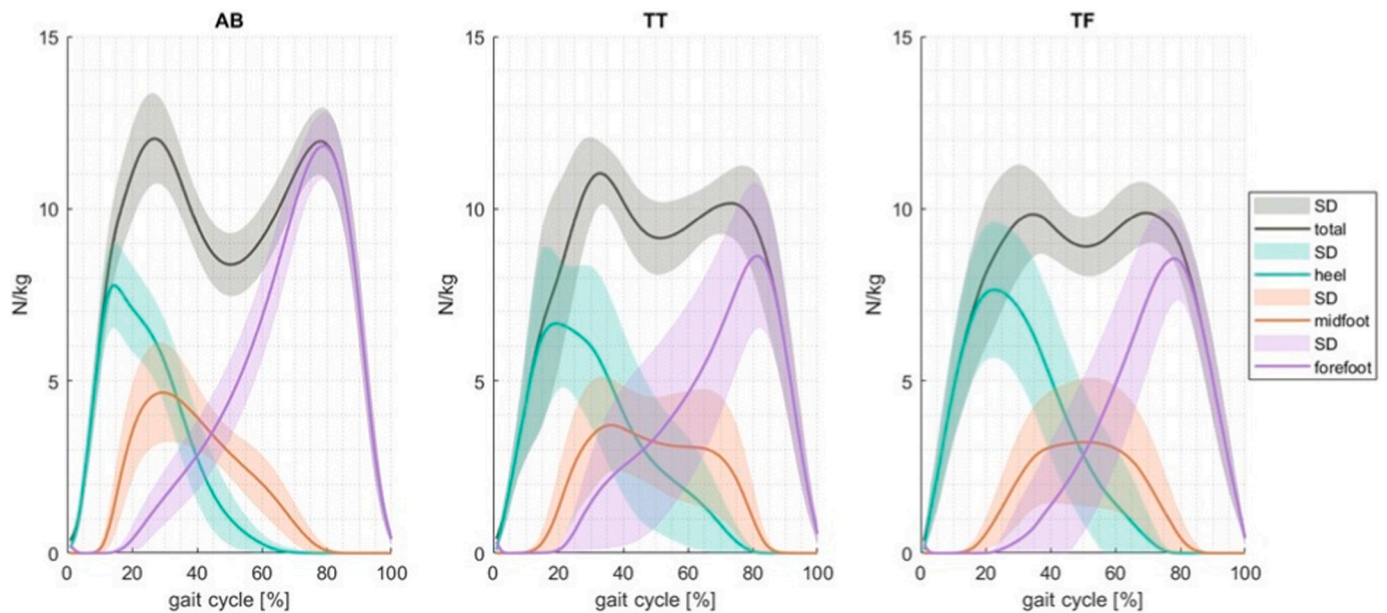


Fig. 3. Comparison of the ground reaction force contributions. Comparison over an averaged gait cycle on the prosthetic side, including heel, midfoot, and forefoot, with the total contribution shown in black. AB group for control, TT for Transtibial, and TF for Transfemoral.

that transtibial amputees who fall have a higher load percentage on the prosthetic limb compared to non-fallers, with postural control deficits observed on the contralateral limb. Additionally, our findings show a shift in the mean CoP towards the contralateral limb, suggesting reduced weight shift to the prosthetic side. To maintain balance, amputees compensate by reducing support time on the prosthetic side [10]. The notable decrease in prosthetic limb support time between TF and TT groups indicates increased asymmetry with higher amputation levels, characterized by a shorter single support phase on the prosthetic side and greater temporal asymmetry.

Our results show a significant increase in mediolateral CoP displacement variability in amputee groups, with no change in the anteroposterior component, aligning with previous studies [1,10,27,31]. King et al.'s [33] imbalance management strategy during single-leg stance includes the ankle couple technique and the shear force technique. The monoaxial nature of the prosthetic foot limits inversion/eversion moments, reducing mediolateral reaction forces and increasing instability during the support phase [33]. This explains the greater mediolateral variability in CoP displacement. The lack of significant differences between TT and TF groups highlights the primary role of lateral ankle stability strategies over prosthetic knee instability in gait adaptations. This underscores the importance of interventions focusing on ankle control, as balance during gait relies heavily on lateral ankle displacement and center of pressure migration [33]. The lack of variation in anteroposterior CoP trajectory is likely due to the unilateral nature of the amputation. Mediolateral variability is more common in unilateral amputees [1,10,27] and unilateral neurological conditions like early-stage Parkinson's disease [34], while bilateral conditions such as multiple sclerosis affect both components [35]. Gaitograms may thus help distinguish between uni- and bilateral functional gait disorders, guiding rehabilitation to focus on compensatory strategies rather than specific pathologies.

CoP displacement analysis highlights distinct compensations for TF and TT amputees, reflecting the impact of amputation level. Seliktar et al. [36] emphasize that anteroposterior GRF variations are crucial for assessing gait quality and amputee confidence in using their prosthesis. TT amputees spend more time braking than propelling with their prosthetic limb, affecting double support phase management. Vanicek et al. [32] find that TT amputee fallers exhibit greater double support phase asymmetry, with increased prosthetic side support and lower knee

extension moments, indicating instability management issues. TT amputees mitigate fall risk by increasing intact limb support time, using a flat-foot strategy instead of heel strike on the prosthetic side. Our results align with these findings, showing that TT amputees prefer a safer midfoot strike over heel strike. The absence of sensory feedback, combined with the limited surface area of the prosthetic foot's heel, contributes to the stabilizing nature of the midfoot strike [32].

The step strike strategy in TF amputees shows distinct patterns. Schmalz et al. [37] report that TF amputees prefer heel strike on the prosthetic side, even with alignment changes. Similarly, Sapin et al. [38] observe that various prosthetic knees lead to heel strike during the support phase for safety. Our results confirm that TF amputees use a pronounced heel strike strategy at the start of the prosthetic support phase. This preference is linked to prosthetic knee function, as heel strike helps lock the knee in extension. Möller et al. [39] find that heel strike increases cortical activity due to sensory processing, decision-making, and motor control demands, with reduced activity when using a microprocessor-controlled knee compared to a mechanical one. TF amputees, therefore, often favor heel strike for added safety.

In summary, transtibial (TT) and transfemoral (TF) amputees exhibit significant differences in gait strategies due to the segments lost. TT amputees favor a midfoot strike to enhance stability, compensating for the lack of sensory feedback and the reduced mobility of the prosthetic foot [8,35]. In contrast, TF amputees tend to adopt a heel strike to lock the prosthetic knee in extension [8,40,41]. TF amputees also demonstrate greater mediolateral variability in center of pressure (CoP) displacement, reflecting lateral instability and limited knee control, whereas TT amputees benefit from improved stability due to residual joint functionality [36]. Temporal asymmetries are more pronounced in TF amputees, who spend less time on their prosthetic limb, compared to TT amputees, who maintain slightly more symmetrical support [8,17,30,34]. These differences highlight the need for personalized rehabilitation approaches tailored to the specific requirements of each group [8,17,24,30,36].

These findings can be applied in clinical rehabilitation to tailor therapeutic strategies according to the level of amputation. For TT amputees, interventions should focus on training to correct midfoot strike to heel strike, improving postural control and enhancing propulsion, with the aim of reducing gait asymmetry [8,35]. For TF amputees, exercises targeting prosthetic knee stability and weight transfer can help

reduce temporal asymmetry and increase prosthetic limb support time [8,40,41]. The mediolateral variability of the center of pressure (CoP) highlights the need for specific work on lateral stability, incorporating contralateral ankle control exercises and prosthetic adjustments in the frontal plane [36]. Gait parameters, such as temporal asymmetries and CoP variations, should be monitored regularly to adjust rehabilitation goals and reduce the risk of falls [8,17,30]. These personalized approaches help improve patient safety, mobility, and quality of life [8,17,24,30,36].

Our study has several limitations. We analyzed only 10 gait cycles due to incomplete gaitograms and lacked subgroup analyses by prosthetic components due to a small sample size. Additionally, data on prosthetic alignment specifics were not available, though alignments were validated as optimal [37,38,40].

5. Conclusion

In conclusion, amputation level significantly impacts cautious walking criteria and gait asymmetry. Higher amputation levels are linked to increased cautious walking criteria and asymmetry. CoP displacement analysis provides insights into how amputation level affects gait, emphasizing the role of prosthetic knee management and motor control loss. Understanding this relationship is crucial for effective rehabilitation, distinguishing compensatory mechanisms from gait abnormalities, and monitoring gait quality beyond rehabilitation.

Ethics statements

Data collection and analysis were conducted in accordance with reference methodologies MR004 (ClinicalTrials.gov ID NCT05803317). Approval was granted by our Institutional Review Board which provides an ethical opinion and a commitment to compliance within the framework of the MR004 methodologies. In accordance with the Declaration of Helsinki, all participants provided written consent for participation.

Consent for publication

Informed consent for publication was obtained from the participants as part of the informed consent before starting the study.

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None

CRediT authorship contribution statement

Pradon Didier: Writing – review & editing. **Dupeyron Arnaud:** Writing – review & editing. **Reneaud Nicolas:** Writing – review & editing, Validation, Methodology, Formal analysis. **Pantera Eric:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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