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Abstract

Objective: Using a 3-degree-of-freedom (DOF) prosthetic foot with lateral and toe joint compliance, this study aims to evaluate the combined effects these features in prosthetic gait through gait trials on 10 non-amputated individual. Results: The addition of coronal and toe compliance had significant kinematic and muscular effects. Notably, this compliance combination reduced peak pelvis obliquity by 27%, preserved the swing stance/ratio, and decreased gluteus medius's activation by 34% on the non prosthetic side, compared to the laterally rigid version of the prosthesis without toe compliance. Conclusions: The results underscore the importance of integrating coronal and toe compliance in prosthetic feet designs as they shows potential in improving gait metrics related to mediolateral movements and balance, while also decreasing muscle activation. Still, these findings remain to be validated in people with transtibial amputations.

The Combined Role of Coronal Compliance With Toe Joint in Transtibial Prosthetic Gait: A Study in Non-Amputees

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ABSTRACT —Objective: Using a 3-degree-of-freedom (DOF) prosthetic foot with lateral and toe joint compliance, this study aims to evaluate the combined effects these features in prosthetic gait through gait trials on 10 non-amputated individual. Results: The addition of coronal and toe compliance had significant kinematic and muscular effects. Notably, this compliance combination reduced peak pelvis obliquity by 27%, preserved the swing stance/ratio, and decreased gluteus medius's activation by 34% on the non prosthetic side, compared to the laterally rigid version of the prosthesis without toe compliance. Conclusions: The results underscore the importance of integrating coronal and toe compliance in prosthetic feet designs as they shows potential in improving gait metrics related to mediolateral movements and balance, while also decreasing muscle activation. Still, these findings remain to be validated in people with transtibial amputations.

INDEX TERMS Compliance, Coronal Stiffness, Gait, Toe Joint, Transtibial Prosthesis.

IMPACT STATEMENT Adding lateral compliance and a toe joint to prosthetic foot can significantly impact mediolateral biomechanics including pelvis obliquity and gluteus medium activation.

I. INTRODUCTION

THE rate of limb amputations is expected to rise in the coming decades due to the increasing prevalence of diabetes, obesity, and trauma. By 2050, it is estimated that over 3.6 million people in the U.S. alone will be living with an amputation [1]. Current prosthetic leg designs primarily focus on sagittal plane movements, aiming for stable walking in that direction. However, amputation also significantly impacts coronal plane gait stability, which is greatly reduced when using a lower limb transtibial prosthesis [2].

In individuals with amputations, inversion, and eversion torques are either altered or absent. This leads to challenges in lateral balance control during walking, as the frontal adjustments of the center of mass and center of pressure are disrupted. Additionally, most prosthetic devices prescribed today have limited flexibility in the coronal plane, resulting in patients developing compensatory gait patterns to walk efficiently and safely [3]. These adaptations often include increased step width [4] and reduced stance time on the prosthetic side. Such gait changes increase the risk of long-term conditions like osteoarthritis, chronic pain, and deep tissue injuries due to the asymmetrical load distribution [5], [6].

Similarly, the metatarsophalangeal (MTP) joint is crucial in walking, as it contributes significantly to push-off during the late stance phase. The extension and flexion of this joint during walking can affect stability, range of motion, walking speed [7], and energy expenditure [8]. Despite its importance, the MTP joint is often excluded in many transtibial prosthetic designs, and only a few studies have explored its impact on lower limb prosthesis users [9], [10].

Research has shown that incorporating a flexible forefoot or independent toe joint into prosthetic designs can improve user satisfaction and enhance gait stability [11]. Moreover, the absence of push-off, a consequence of amputation, increases the risk of asymmetrical gait and osteoarthritis, particularly in the non-amputated limb [9]. Interestingly, toe joint stiffness can have as much or even more influence in the center of mass dynamics compared to ankle stiffness [10], where much of the design optimization in prosthetics currently focuses.

Currently, the understanding of how lateral compliance affects prosthesis users is limited, beyond its role in improving stability and reducing balance-related effort on uneven surfaces [12]. The effect of lateral compliance in transtibial gait has been evaluated in tasks other than baseline ambulation in straight, even and non-inclined walking, with studies focusing on tasks that functionally involve the use of ankle inversion and eversion as turning [13], stair ascent [14], ambulation in uneven ground [14] or gait in crossed slopes' [15]. In addition, these studies evaluated the effect of lateral compliance in the absence of a toe joint, that, as previously mentioned, has been shown to significantly affect gait in people with transtibial amputation.

The objective of this work is to assess the combined effect of including lateral compliance and a toe joint to a transtibial prosthesis on human biomechanics. Using our previously developed multiaxis passive three-degree of freedom transtibial prosthesis [16], we conducted experiments that explore the impact of coronal and toe compliance on spatiotemporal variables, kinematics, ground reaction forces, and muscular activation in non-amputated participants through a set of gait trials under various compliance conditions. This paper presents the experiment's design and results, discussion on the obtained results in terms of gait biomechanics, and serves as a comparison point for future assessments in people with amputations.

II. RESULTS

Joint kinematics and moments are presented in figures 1 and 3. In addition, the median and interquartile ranges of the spatiotemporal and kinematics metrics with their corresponding Friedmann test and post hoc comparison are shown in table I. Peak ground reaction forces and moments are presented in table II. The results compare the outcomes of walking on flat terrain with the following conditions: NT-NL: no toe compliance, and no lateral compliance; T-NL: with toe compliance, but no lateral compliance; NT-L: no toe compliance, but with lateral compliance and T-L: with both toe compliance and lateral compliance.

A. *Spatiotemporal Variables*

We found significant differences in both the stance time and stance/swing ratio between the baseline condition (NT-NL) and the conditions involving the use of toe compliance. As observed in table I and figure2a and b, there was a significant reduction of the stance time in both the T-NL and T-L conditions of 9% and 12% respectively. Moreover, the stance/swing ratio was also affected by the use of a compliant toe joint, however, a significant reduction of 8.5% was only observed when the toe joint was used alone. On the other hand, the addition of toe and/or lateral compliance did not affect gait speed, swing time, step width, step length, or stride length when compared to walking with a toe and laterally rigid prosthesis.

B. *Kinematics and Range of Motion*

The addition of coronal and toe compliance to the prosthetic foot mostly affected the ankle and pelvis kinematics of the participants. In the sagittal plane, the addition of compliant toes significantly increased the peak ankle dorsiflexion angle in 24% and 27% respectively for the T-NL and T-L conditions compared to a completely rigid foot as seen in figure 1. We also found a main effect for peak plantarflexion angle across the conditions. The flexible toes trials show a reduction in the peak plantarflexion angle regardless of the use of lateral compliance, nevertheless, this effect was not significant for the pairwise comparisons.

Significant effects were also found in the coronal plane. As seen in table I the maximum ankle eversion angle was significantly higher for the T-L condition (figure 2c). In addition, this particular compliance combination significantly decreased maximum pelvis obliquity, as seen in figure 2e. On the other hand, knee and hip kinematics were mostly unaffected by the differences in mobility or compliance of the prosthetic device in the different trials.

Regarding the range of motion (ROM), there was a significant increment in the ankle coronal ROM for the conditions where lateral mobility was present, with an increase of 31% and 16% compared to the baseline condition (figure 2d). Additionally, the pelvis coronal range of motion tended to decrease with the addition of both lateral and toe compliance. Moreover, the use of a compliant forefoot in the prosthesis (T-NL and T-L) significantly decreased the sagittal range of motion in about 3°, which was not observed for the NT-L condition. Lastly. the knee ROM was not unaffected by the use of lateral and/or toe compliance in the participants.

C. *Ground Reaction Forces and Moments*

The peak ground reaction moment in the mediolateral direction was found to be significantly higher for the prosthetic foot that includes lateral compliance only (NT-L). In this condition the participants exerted 0.07 Nm/kg more than in the baseline condition (NT-NL) which represents a difference of 14.5%. It can also be observed that the use of toe compliance tends to reduce the peak mediolateral moment when comparing the pairs of conditions that differ only in the use of this degree of freedom (NT-NL Vs T-NL and NT-L Vs T-L). This apparent decrease opposes the effect of lateral compliance in the T-L condition which, as observed in table II, is not significantly different from the NT-NL condition despite being also laterally compliant.

In addition, we found a main effect for lateral compliance in the peak anterior-posterior moment, which tends to be smaller for the NT-L and T-L conditions. Surprisingly, there is no noticeable effect of the use of flexible toes between conditions in the peak sagittal moments, even though the toes are being compressed in this direction during gait. Lastly, there is no observable effect of lateral and toe compliance in peak ground reaction forces, except for a decrease in the peak mediolateral force in the NT-L condition compared to the NT-NL condition (0.61 N/kg Vs 0.70 N/kg).

D. *Electromyography*

The different compliance and mobility conditions exerted a significant effect on the activity of the gluteus medius (figure 2f) on the non-prosthetic side and in the vastus lateralis and hamstrings on the prosthetic side (table II). The activity of the gluteus medius, which plays a major mediolateral role during gait and controlling pelvis stabilization and posture, decreased as mobility increased, as observed in figure 2f. We observed a decrease of 0.17 μV in the T-NL condition, which seems to be enhanced by the use of lateral compliance, leading to a further decrease of 34% for the T-L condition compared to the

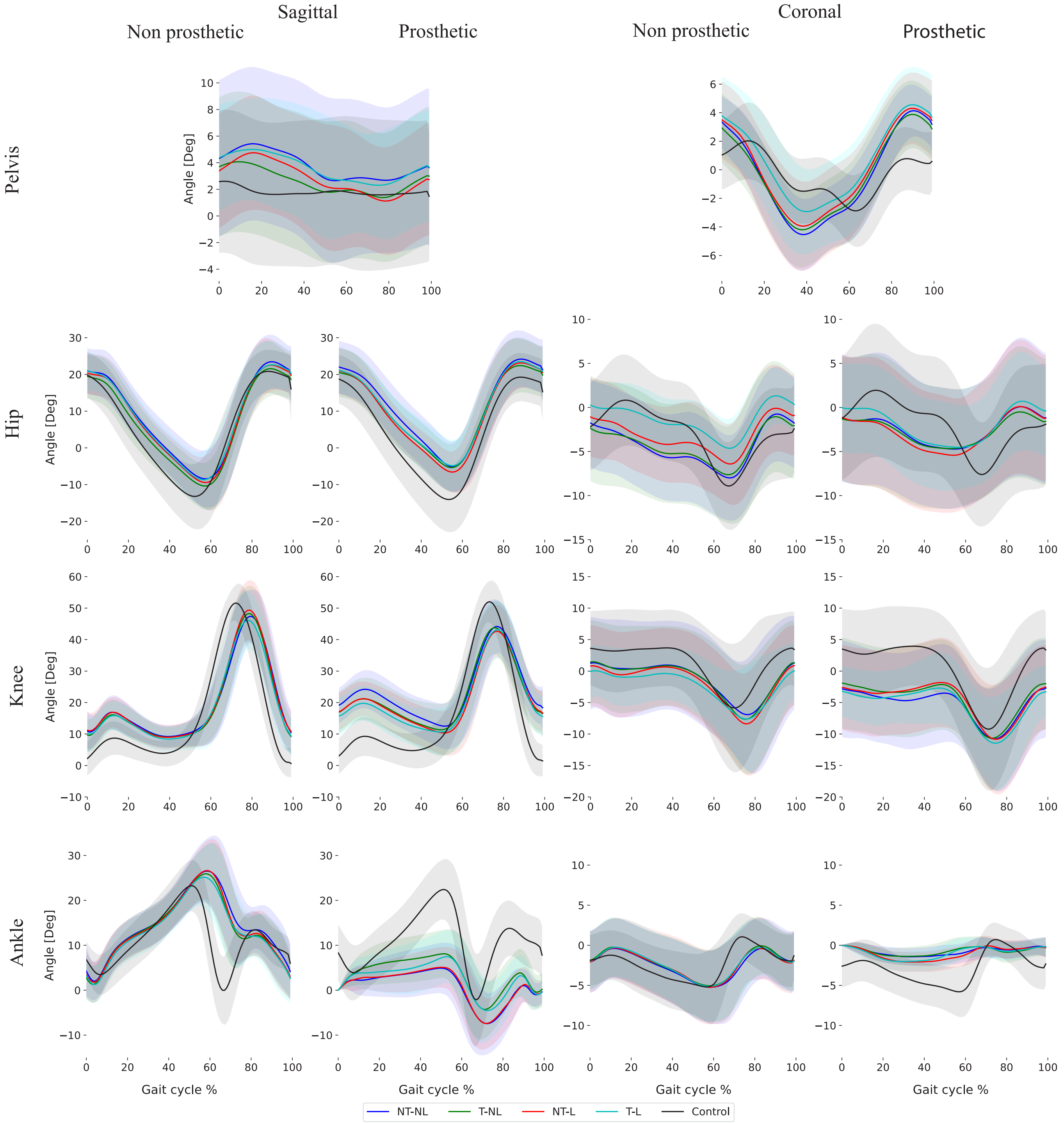
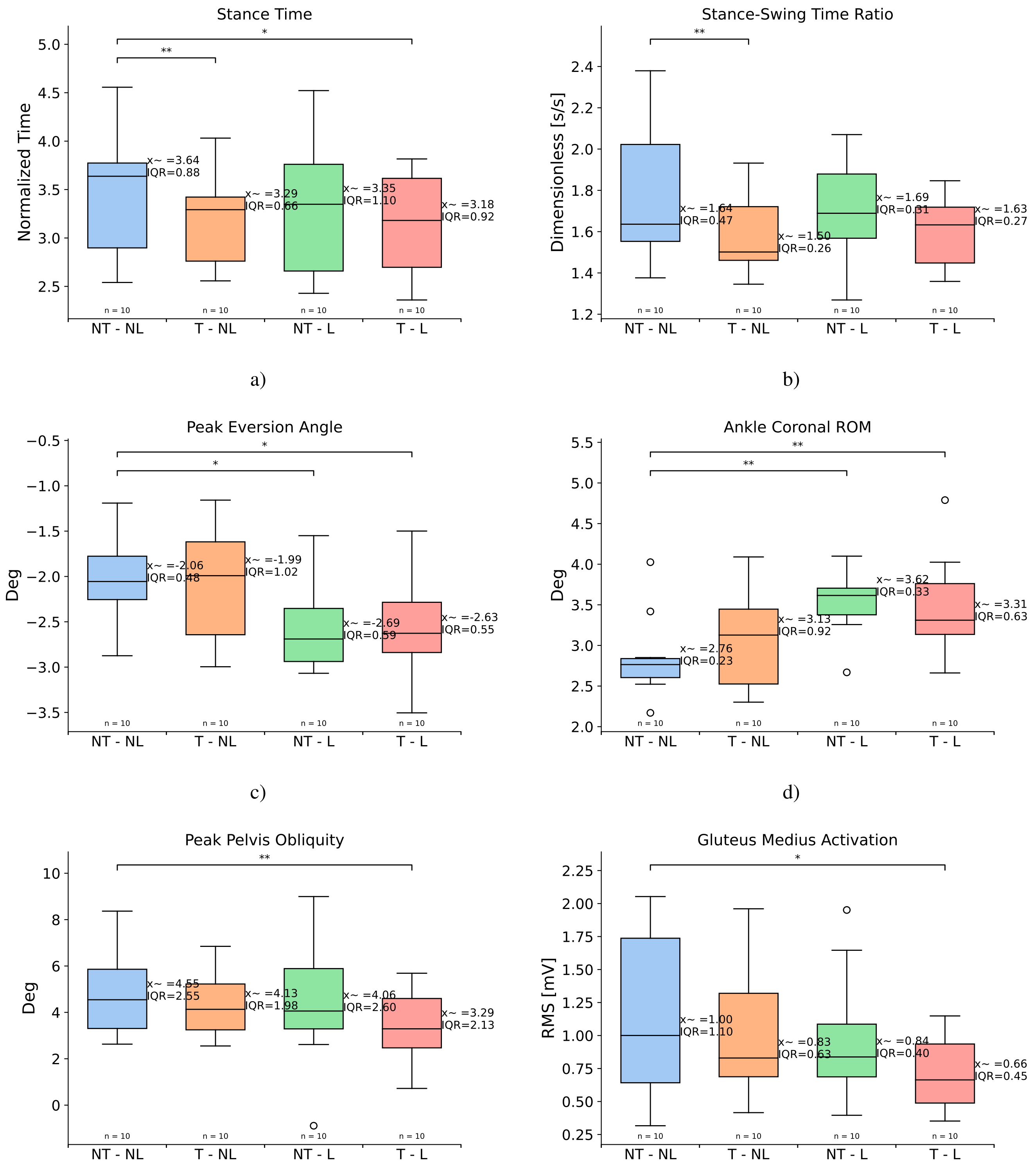


Fig. 1: Pelvis, knee, hip and ankle kinematics in the sagittal and coronal plane under the different compliance conditions during the gait trials. The control curve, shown in black, corresponds to barefoot walking.



a) b)

c) d)

e) f)

Fig. 2: Spatiotemporal, kinematic and muscular variables significantly affected by the combined use of lateral and toe compliance during the gait trials. a)Stance time, b)Stance/swing ratio, c) Peak eversion Angle, d) Ankle coronal range of motion, e) Peak pelvis obliquity, f) Gluteus medius average RMS

TABLE I: Obtained spatiotemporal and kinematic variables for the different foot conditions. The corresponding Friedmann and Wilcoxon p-values are shown.

Metric	Conditions - Median (IQR)				Friedmann		Wilcoxon (p-value)		
	NT-NL	T-NL	NT-L	T-L	F	p-value	NT-NL Vs T-NL	NT-NL Vs L-NT	NT-NL Vs T-L
Spatiotemporal									
Gait Speed (m/s)	0.46 (0.17)	0.49 (0.12)	0.49 (0.20)	0.50 (0.17)	1.56	0.6684			
Stance Time	3.64 (0.88)	3.29 (0.66)	3.35 (1.10)	3.18 (0.92)	8.28	**0.0405**	**0.009**	0.375	**0.0136**
Swing Time	1.85 (0.42)	1.94 (0.39)	1.88 (0.38)	1.88 (0.41)	3.0	0.391			
Ratio Stance-Swing	1.64 (0.47)	1.50 (0.26)	1.69 (0.31)	1.63 (0.27)	8.2	**0.040**	**0.0058**	0.322	0.064
Step width	0.12 (0.02)	0.12 (0.02)	0.12 (0.01)	0.12 (0.02)	1.07	0.781			
Step Length	0.43 (0.07)	0.44 (0.05)	0.45 (0.06)	0.44 (0.07)	2.64	0.45			
Stride Length	0.81 (0.12)	0.83 (0.06)	0.84 (0.09)	0.83 (0.16)	0.359	0.948			
Kinematics (**Deg**)									
Peak dorsiflexion	7.22 (4.62)	9.01 (3.72)	6.00 (4.37)	9.18 (5.59)	13.79	**0.0031**	**0.019**	0.556	**0.048**
Peak plantarflexion	8.29 (6.25)	5.95 (4.20)	8.57 (3.81)	5.69 (4.22)	8.76	**0.0169**	0.25	0.91	0.128
Peak inversion	0.80 (0.20)	0.91 (0.55)	1.05 (0.42)	0.78 (0.42)	1.44	0.696			
Peak eversion	2.06 (0.48)	1.99 (1.02)	2.69 (0.59)	2.63 (0.55)	8.87	**0.0309**	0.921	**0.019**	**0.013**
Peak knee flexion	47.65 (7.28)	45.16 (8.74)	46.28 (7.80)	44.16 (11.17)	7.56	0.056			
Peak hip flexion	26.33 (14.62)	22.36 (12.88)	23.31 (10.01)	24.75 (8.03)	2.4	0.493			
Peak hip extension	4.64 (9.02)	6.40 (6.93)	7.88 (3.26)	5.98 (5.57)	4.68	0.196			
Peak hip abduction	2.73 (6.84)	1.41 (3.95)	3.07 (6.64)	3.15 (4.34)	3.24	0.356			
Peak hip adduction	5.66 (5.92)	6.26 (5.45)	6.01 (5.88)	6.46 (5.81)	2.76	0.43			
Max. pelvis tilt	5.86 (4.25)	4.22 (2.91)	5.34 (3.47)	6.55 (2.36)	0.356	0.948			
Max. pelvis obliquity	4.55 (2.55)	4.29 (1.98)	4.06 (2.60)	3.29 (2.13)	8.756	**0.032**	0.431	0.845	**0.0019**
ROM (**Deg**)									
Ankle Sagittal ROM	15.76 (1.54)	16.02 (2.12)	15.04 (1.95)	15.39 (3.82)	4.32	0.228			
Ankle Coronal ROM	2.76 (0.23)	3.13 (0.92)	3.62 (0.33)	3.31 (0.63)	17.28	**0.0006**	0.322	**0.0019**	**0.0019**
Knee ROM	38.00 (8.39)	37.78 (7.85)	36.74 (7.68)	38.03 (9.39)	2.28	0.516			
Hip Sagittal ROM	33.13 (4.37)	29.62 (3.70)	32.05 (5.23)	30.40 (4.73)	12.23	**0.003**	**0.019**	0.921	**0.048**
Hip Coronal ROM	7.96 (2.17)	7.96 (1.91)	8.22 (3.20)	8.61 (1.85)	4.19	0.24			
Pelvis Sagittal ROM	5.41 (2.03)	4.58 (0.76)	5.14 (1.34)	4.77 (1.25)	5.4	0.144			
Pelvis Coronal ROM	9.21 (0.97)	8.82 (0.75)	8.64 (1.81)	8.65 (1.26)	7.91	**0.047**	**0.0273**	**0.048**	**0.019**

baseline foot. However, the reduction effect is only significant for the T-L condition.

Regarding the prosthetic side, we found significant differences in muscles involved in the control of gait and balance in the sagittal plane. In particular, the vastus lateralis and hamstrings presented a significant reduction in their activity for the T-NL condition of 8% and 12% respectively. This decrease, which can be attributed to the compliant toes, was not observed in the T-L condition and might have been occluded by the joint use of lateral compliance. The activity of the gluteus medius and gluteus maximum did not show significant changes with increased compliance. Lastly, the variability of the muscular activity was not affected by the compliance and mobility combinations on either the prosthetic or non-prosthetic sides.

III. DISCUSSION

Contrary to other studies showing no effect of a compliant forefoot in spatiotemporal variables [11], [17]–[19], this study found a significant reduction in the stance time by the use of compliant toes. However, the combined use of toe and lateral compliance seems to prevent a subsequent decrease in the

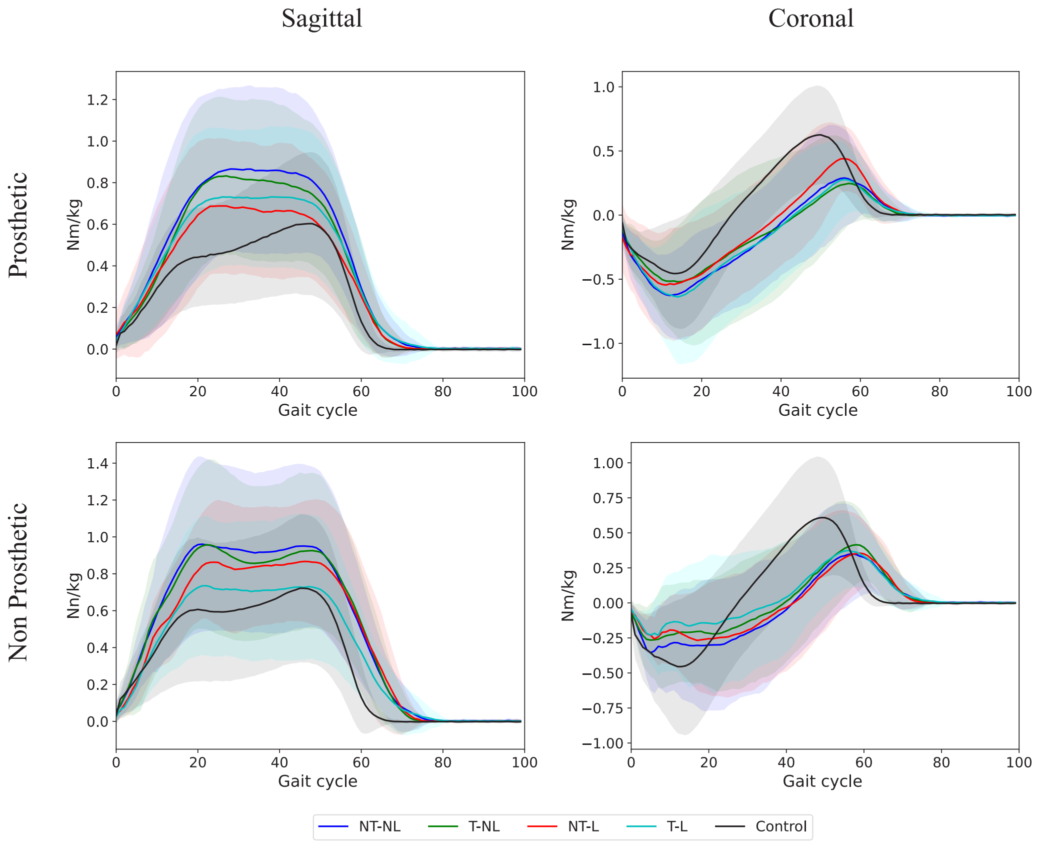


Fig. 3: Ground reaction moments in the sagittal and coronal plane under the different compliance conditions during the gait trials. The control curve, shown in black, corresponds to barefoot walking.

stance/swing ratio, found within the normal values for able-bodied participants of 1.61 ± 4% [20], except for compliant toes only (T-NL) table I. This has the potential to mitigate the asymmetric stance/swing ratio that characterizes prosthetic gait, who show a significantly decreased ratio in the prosthetic side [21]. In line with other studies, we found no major changes in other spatiotemporal variables associated with flexible toes [11], [17], in combination with lateral compliance.

For the T-L condition, the peak inversion did not show any significant changes while the peak eversion angle was significantly increased. This matches the previously observed increase in mobility for other laterally compliant prosthetic feet and might obey the decrease in the overall foot stiffness [13]. In addition, the increase in the coronal ROM of the ankle for this condition indicates that the prosthetic users might be prone to naturally use additional coronal compliance, if available, even for straight non-inclined gait as previously investigated [14]. This can benefit the users in terms of stability and balance, as well as provide potential surface adaptation. In the sagittal plane, increased peak dorsiflexion angles in the T-L condition were also observed in other feet with flexible forefoot sections [10], [17], [18]. In this study, however, the increased peak dorsiflexion was not accompanied by an increase in the ankle sagittal range of motion, as it can be seen in table I.

For the pelvis, providing either coronal or toe mobility for prosthetic feet alone did not result in significant changes in the pelvis peak angles. Instead, we found a significant decrease in the pelvis obliquity as a product of the combined effect of flexible toes and lateral compliance. Pelvis obliquity was reduced by 27% in this condition compared to the NT-NL and is closer to the median values for pelvis obliquity reported in non-amputees of about 2° [22]. This effect, in combination with the significant reduction in the activity of the gluteus medius for the same condition, suggest that both a flexible forefoot and a coronally compliant ankle capable of exerting mediolateral torque are required for improved pelvis stability in prosthetic gait. Reducing peak obliquity could impact the “hip hiking” strategy of lower limb prosthetic gait [23], [24] and also, offer some benefits as decreased vertical loads [24] and improved limb forward progression and energy recovery [23].

Regarding the ground moments, we consider that the combined use of flexible toes and lateral compliance can decrease the overall foot effective stiffness and reduce the observed moment in the anterior-posterior plane. It is possible that the chosen stiffness for the toes is sufficiently stiff to avoid a decrease in the effective foot length [10], leading to no significant changes in the peak anterior-posterior moment previously reported for prosthetic feet with flexible forefoot [15]. In the coronal plane, the significant increase in the peak mediolateral moment in the NT-L condition but not in the L-T condition can be related to the properties of the toes.

We consider that the combined use of flexible toes with a

TABLE II: Obtained ground reaction forces, moments, and RMS from electromyography signals for the different foot conditions. The corresponding Friedmann and Wilcoxon p-values are shown.

Metric	Conditions - Median (IQR)				Friedmann		Wilcoxon (p-value)		
	NT-NL	T-NL	NT-L	T-L	F	p-value	NT-NL Vs T-NL	NT-NL Vs L-NT	NT-NL Vs T-L
Ground Reaction Moments $(\mathbf{Nm \cdot kg^{-1}})$									
Peak A-P Moment	1.02 (0.24)	0.98 (0.23)	0.76 (0.36)	0.89 (0.33)	8.03	**0.045**	0.769	0.064	0.769
Peak M-L Moment	0.48 (0.20)	0.40 (0.28)	0.55 (0.20)	0.45 (0.14)	11.75	**0.007**	0.492	**0.0058**	0.55
Ground Reaction Forces $(\mathbf{N \cdot kg^{-1}})$									
Peak A-P Force	1.12 (0.22)	1.03 (0.31)	1.02 (0.44)	1.19 (0.51)	2.03	0.564			
Peak M-L Force	0.70 (0.16)	0.69 (0.10)	0.61 (0.19)	0.66 (0.13)	4.43	0.217			
EMG Prosthetic side $(\mu\mathbf{V})$									
RMS Gluteus Medius	0.60 (0.76)	0.66 (0.70)	0.58 (0.62)	0.80 (0.69)	1.94	0.58			
RMS Vastus Lateralis	0.95 (0.21)	0.87 (0.32)	0.92 (0.26)	1.05 (0.87)	5.4	0.144	**0.0195**	0.083	0.845
RMS Hamstrings	1.63 (0.54)	1.42 (0.72)	1.13 (0.62)	1.56 (0.57)	6.24	0.1	**0.048**	0.16	0.083
RMS Gluteus Maximus	0.26 (0.12)	0.30 (0.08)	0.35 (0.10)	0.31 (0.08)	2.33	0.506			
EMG Non-Prosthetic side $(\mu\mathbf{V})$									
RMS Gluteus Medius	1.00 (1.10)	0.83 (0.63)	0.84 (0.40)	0.66 (0.45)	6.96	0.07	0.55	0.49	**0.037**
RMS Vastus Lateralis	0.73 (1.10)	0.72 (0.49)	0.63 (0.56)	0.55 (0.62)	2.73	0.434			
RMS Hamstrings	1.63 (1.38)	1.95 (1.60)	1.87 (1.15)	1.94 (1.03)	1.79	0.614			
RMS Gluteus Maximus	0.53 (0.32)	0.33 (0.25)	0.33 (0.34)	0.32 (0.27)	3.12	0.373			

laterally compliant joint can reduce the exerted mediolateral moment by the ankle due to the mechanical properties of the toes' material, as it could partially dampen the forces exerted during the gait cycle. This issue should be considered in the design of multi-axial transtibial prostheses with multiple degrees of freedom. Still, the ability to exert significantly more lateral angular moment in the NT-L condition offers some potential benefits to the users, mostly related to balance [13]. Lastly, to the best of our knowledge, this is the first study to investigate the combined effect of lateral compliance and toe joint in anterior-posterior ground reaction forces and moments. In this study, we found no effect in the sagittal forces and a significant effect in the sagittal moments.

On the prosthetic side, and contrary to the expected increase in muscular activation due to increased prosthetic foot compliance [25], [26], toe compliance resulted in decreasing the activity of the vastus lateralis and hamstrings. We attribute this effect to the additional push-off provided by the toes, which supports the role of both muscles in the generation of vertical and forward movements [27]. However, it is unclear why this effect was significant only for the T-NL condition and not the T-L condition as well. Still, we can observe a reduced median RMS value for the NT-L and T-L conditions. This toe effect could be favorable to transtibial prosthesis users, as it is reported that prosthesis users relied significantly more on their hamstrings and gluteus maximus to generate power in the prosthetic limb [25]

Regarding Gluteus maximus and gluteus medius, these muscles' activity seems not to be affected in the gait of transtibial prostheses users who use prostheses without coronal mobility in either gait analysis or simulations [25], as their main role is found in the coronal plane. In this plane however, we found a significant reduction in the activity of the gluteus medius for the T-L condition for the non-prosthetic side, which has been reported to be significantly increased during all phases of the gait cycle for people with transtibial amputation [28]. As

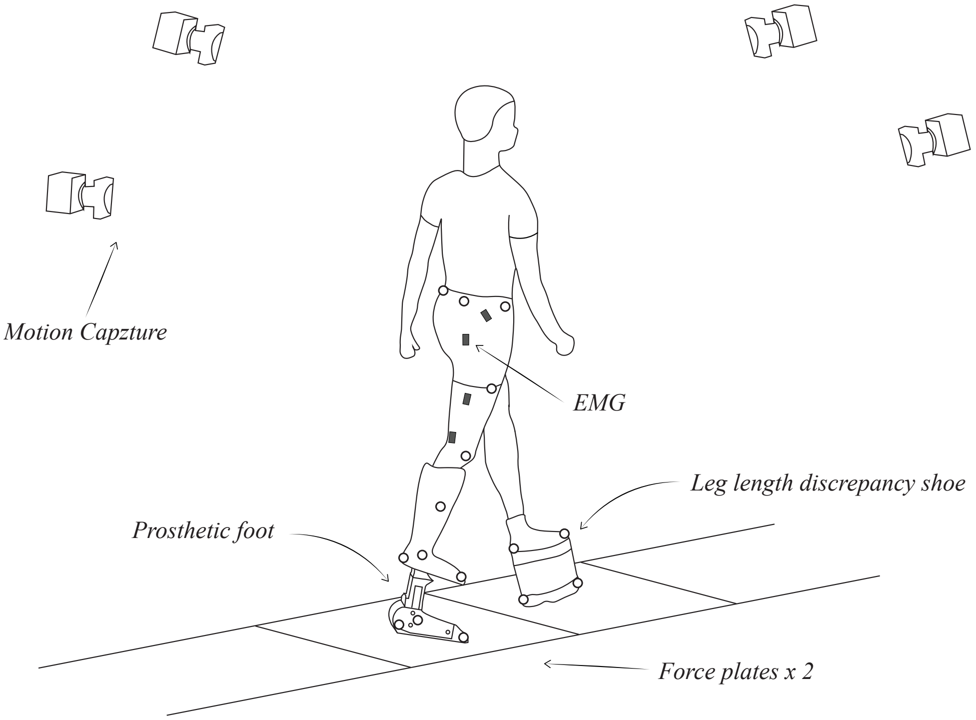


Fig. 4: Experimental setup for the gait trials. We obtained Kinematics, ground reaction forces and electromyographic signals from the participants walking with the different prosthetic feet variants

pelvis support is one of the roles of gluteus medius stance [29] our results support the idea that the combination of a flexible toe joint and lateral compliance can reduce the user's effort in stabilizing the pelvis during stance.

Several limitations of this study must be acknowledged. First, the dorsiflexion and plantarflexion stiffness was fixed at 5.63 Nm/deg, offering an adequate torque of 1.2 Nm/kg [30]. However, the masses of the experimental participants varied from 47 to 75 kg, potentially influencing sagittal plane responses and data variability, despite the normalization of kinetic variables to body weight. Second, using prosthesis simulators and leg discrepancy shoes allowed testing in non-amputated individuals, but altered their anthropocentric proportions, such as leg length and perceived balance [10].

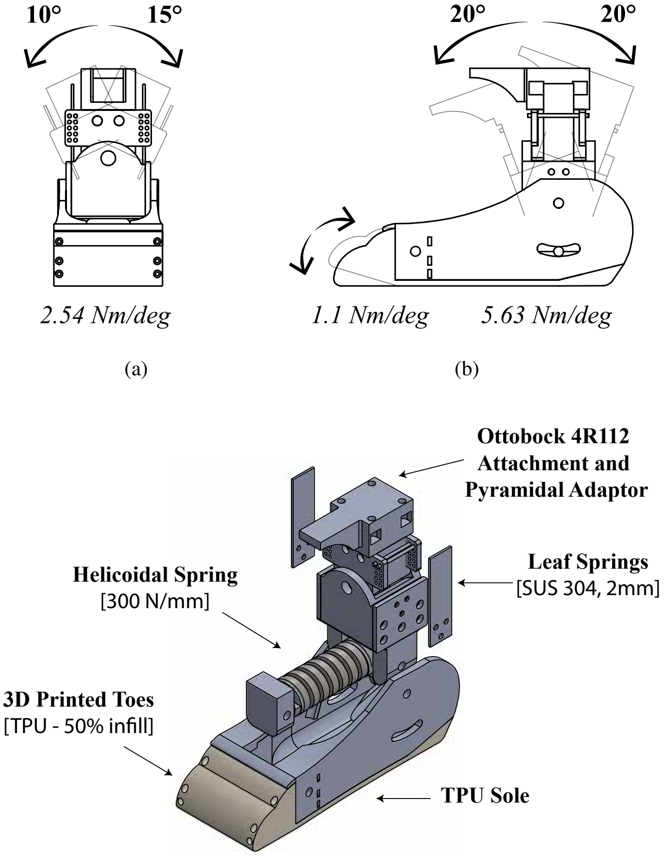
Although previous studies reported no significant effect on gait parameters except for ground reaction forces [31], we maintained a consistent height adjustment of 24.5 cm. Lastly, lower limb symmetry was not fully considered due to hardware differences, which affects the reliability of comparisons. This combined effect of toe and coronal compliance on gait symmetry requires further investigation. Lastly, it remains uncertain if results from non-amputated individuals will fully align with those of with amputations, and future research is needed to explore the clinical implications of these findings for prosthesis design.

IV. CONCLUSION

This study provides insights into the individual and combined effects of coronal compliance and a toe joint in transtibial prosthetic gait, using non-amputees as a preliminary model. The results suggest that the inclusion of these two features can influence spatiotemporal variables, joint kinematics, ground reaction forces, and muscular activity in both the sagittal and coronal planes. Notably, the addition of lateral compliance and a flexible toe joint showed potential in improving balance, decreasing pelvic obliquity, increasing the ankle coronal range of motion, and reducing muscle activation of the gluteus medius, in the non-prosthetic side, compared to a laterally rigid foot without toe compliance. These results underscore the importance of integrating coronal and toe compliance in prosthetic designs to address the biomechanical challenges faced by people with lower-limb amputation. Future studies involving people with amputation are necessary to validate these findings and explore their clinical relevance, particularly concerning long-term gait adaptations and the prevention of secondary musculoskeletal conditions such as osteoarthritis. This research lays the groundwork for advancing prosthetic technology with the goal of improving the utility of lower-limb prostheses.

V. MATERIALS AND METHODS

We conducted a series of gait experiments on non-amputated individuals using a transtibial prosthesis simulator and a leg length discrepancy shoe, shown in figure 6. The participants were asked to walk in a straight, even, non-inclined path, a 10-meter course, at a self-selected speed while performing consecutive steps into two force plates. This was done for a set of trials where the lateral and toe compliance was changed as the subjects wore four variants of a prosthetic foot that include flexible or rigid toes and rigid or a compliant coronal ankle joint. An overview of the experimental setup and the prosthetic foot can be found in figures 5 and 4. Lower limb kinematics,



(a) (b)

(c)

Fig. 5: (a) Frontal, (b) Lateral and (c) Isometric CAD of the prosthetic foot and its components.

ground reaction forces and moments, and electromyographic data were collected to assess the effect of providing compliance in these two degrees of freedom over prosthetic gait. Please refer to the Supplementary Materials for details regarding material and methods, including the experimental hardware, the experimental protocol, data processing and statistical analysis.This study was conducted following a protocol approved by the University of Tsukuba Institutional Review Board (Ethical Committee approval number 2023R754). All participants provided written informed consent prior to participation.

VI. SUPPLEMENTARY MATERIAL

The supplementary materials include the details of the experimental hardware, and prosthetic foot as well as the detailed experimental protocol and the processing of kinematic, kinetic and electromyographical variables. In addition, figures S1-S4 display the box plots for other significant variables presented in tables I and II not shown in the main text.

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(a) (b)

Fig. 6: (a) Leg length discrepancy shoe and, (b) 3-DOF prosthesis with a mounted socket simulator used for the gait trials.

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